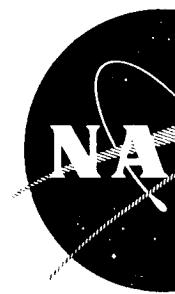


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BRUSHLESS ROTATING ELECTRICAL GENERATORS FOR SPACE AUXILIARY POWER SYSTEMS

by

J. N. Ellis and F. A. Collins

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NO. NAS 3-2783

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LEAR SIEGLER, INC.



POWER EQUIPMENT DIVISION
CLEVELAND 1, OHIO

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THIRD QUARTERLY
REPORT

July 15, 1964

BRUSHLESS ROTATING ELECTRICAL GENERATORS
FOR SPACE AUXILIARY POWER SYSTEMS

Contract No. NAS 3-2783

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J. N. Ellis and F. A. Collins

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SUMMARY

31714

In this quarterly report, design manuals and Fortran computer programs are presented for the following AC generators:

1. Two-Coil, Inside-Coil Lundell or Becky-Robinson Generator
2. Two-Coil, Outside-Coil Lundell
3. Single-Coil, Outside Coil Lundell
4. Rotating-Coil Lundell (Automotive Type)
5. Inside-Coil, Stationary-Coil Lundell.

Design manuals without computer programs are presented for:

6. Permanent-Magnet AC Generators
7. Homopolar Inductor AC Generators
8. Disk-Type or Axial Air-Gap Lundell Generator

An equivalent circuit representation of synchronous AC generators is published with a discussion of its development.

A. E. Fuhs

INTRODUCTION

This study is sponsored by the National Aeronautics and Space Administration under Contract No. NAS3-2783.

The objective as set forth in the NASA work statement introduction is: --- "To advance the technology for the brushless types of rotating electrical generators, specifically for space auxiliary power plants."

A further objective of this study is to provide tools that will allow the reader to select the best generator for a specific application, to calculate the design performance, and to evaluate any contemplated changes in design parameters or materials.

WORK BEING ACCOMPLISHED

Complete design manuals and computer programs are being written for those brushless AC generators that are believed most likely to be considered for space applications and for ground-based applications.

This approach to the study was taken rather than to reject all but two or three generator types on the basis of a superficial examination. Each of the machines presented in this study are considered to have an application area.

In the first quarterly report, design manuals for wound-rotor, salient pole and nonsalient pole generators were published with a Bell computer program for the salient pole generator. Derivations for most of the design formulae were given.

In the second quarterly report, a Fortran computer program for wound pole, salient pole generators was published with the design manual for that generator. The design manual without the computer program was published for the two-coil inside-coil Lundell or Becky-Robinson generator.

Discussions on length-to-diameter ratios, pole-face losses as design limits and motoring capabilities of salient pole generators are also given in the second quarterly report.

In this, the third quarterly report, Fortran computer programs and design manuals are published for the following AC generators:

1. Two-Coil, Inside-Coil Lundell or Becky-Robinson Generator
2. Two-Coil, Outside-Coil Lundell Generator
3. Single-Coil, Outside-Coil Lundell Generator
4. Rotating-Coil Lundell (Automotive-Type) Generator
5. Inside-Coil, Stationary-Coil, Lundell Generator

Design manuals without computer programs are published for:

6. Permanent-Magnet AC Generators
7. Homopolar Inductor AC Generators
8. Axial Air-Gap Lundell Generators

The last three design manuals are to be programmed in Fortran for the final report. And, in addition, a program for Induction generators will be included if time on this contract permits.

Because of the general and widely understood use of the term Lundell, all of the generators discussed in this study that have claw-type or interlocking, finger-type poles are called Lundell generators. To most engineers, the name Lundell describes the rotor pole arrangement. In this report, there is no other basis for the use of the name.

THE NEXT REPORT

The next report is the final report, to be issued in October, and it will consist of two parts. The first part is generator selection criteria and the second part is the electrical design section.

In the first section, the selection criteria, comparison data will be published. Such data will be weight and physical size comparison, evaluations of rotor dynamics, suitability of the various types of generator rotors for use with gas or liquid bearings. Thermal equivalent circuits are to be published in the selection section also.

The second section of the final report will contain the generator design manuals with the Fortran computer programs and the synchronous generator equivalent circuits.

An appendix will be published containing the small studies, discussions and derivations that support the rest of the study.

For each generator design manual, a general approach to the start of a generator design will be provided. It will be similar to that provided for permanent magnet generators in this third quarterly report. Beyond this general approach, the user must select the various design parameters himself. The user of these programs should have some familiarity with AC machine design.

A person unfamiliar with electrical machine design would benefit from a synthesis program that selected the design parameters for the design program inputs, but the time available on this contract does not allow its development.

The design manual has been arranged as a computer program and the sequence of calculations results from storage limitations of the smaller computers (1620).

A number is assigned to a symbol and maintained throughout all of the manuals presented in this Quarterly Report. Where the symbol is not used in a particular manual, the symbol and corresponding number are omitted entirely from the manual.

The symbol number in brackets wherever found means the symbol and not the value of the number itself. Numbers without brackets are numerical values.

A symbol list with corresponding design manual calculation numbers, Fortran program symbols and the definition of the symbols is given at the beginning of the manual.

The design equations in the manual are written with symbols and are repeated with the bracketed numbers that locate the symbol definition in the symbol list.

Following the design equations, the Fortran program is published with the same identifying equation numbers found in the design manual.

NOTE ON WINDAGE CALCULATIONS

In each design manual there is a statement to the effect that there is no known satisfactory method of calculating windage. That, of course, is open to challenge and probably should read "we know of no". The formula given is crude and is only intended for use in standard air.

For gases or fluids other than standard air, the fluid density and viscosity must be considered. The formula given in the manual can be modified by the factors

$$\left(\frac{\rho}{.0765}\right)^{.8} \left(\frac{u}{.0435}\right)^{.2}$$

where

ρ = density - Lbs FT⁻³

μ = viscosity LBS FT⁻¹ HR⁻¹

.0765 = density std. air

.0435 = viscosity Std air

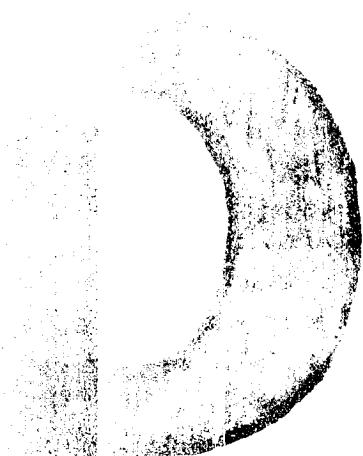
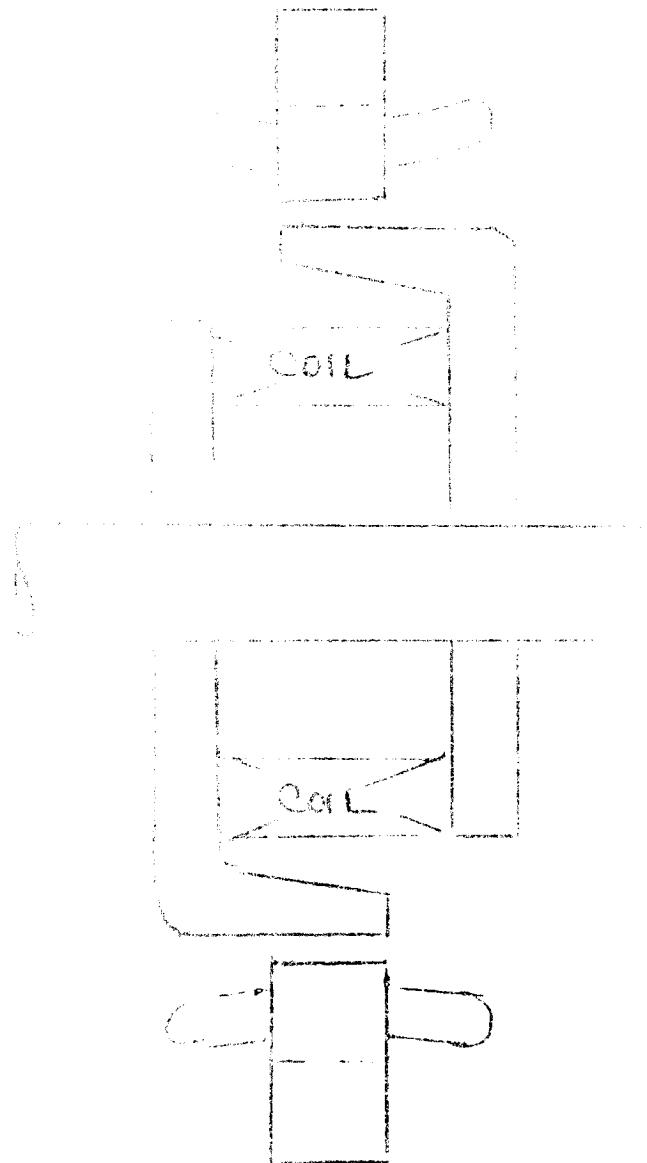
The above relationship can be arrived at by referring to Shepherd "Principles of Turbomachinery", Macmillan Pub. Company. See page 152. The friction factor for turbulent flow is a function of

$\frac{1}{(R_e)^{.2}}$ and the loss is a function of $\frac{\rho}{(R_e)^{.2}}$ times a constant for a fixed velocity and fixed dimensions. The correction for a gas other than standard air, since $R_e = \frac{DV\rho}{\mu}$, would be

$$\frac{\rho}{\rho_{air}} \cdot \left(\frac{\rho_{air}}{\rho}\right)^{.2} \cdot \left(\frac{u}{u_{air}}\right)^{.2} \quad \text{or} \quad \left(\frac{\rho}{.0765}\right)^{.8} \left(\frac{u}{.0435}\right)^{.2}$$

THEORY OF THE
WIDELUND COIL

COILS SIMILARLY USED IN AL

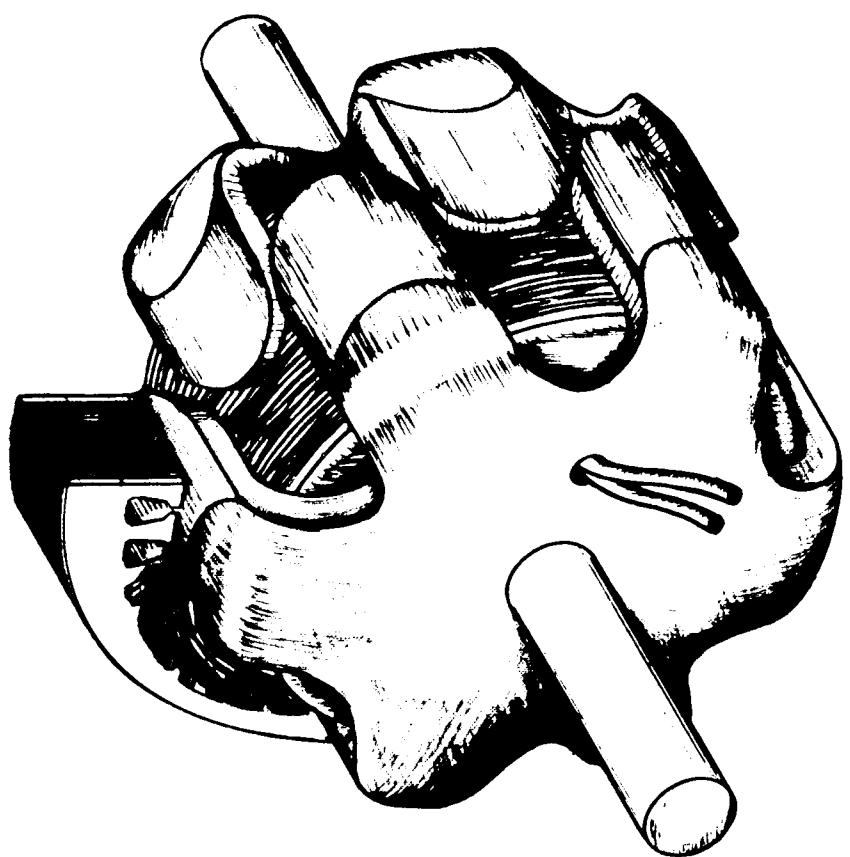


INSIDE-COIL, ROTATING-COIL LUNDELL GENERATOR

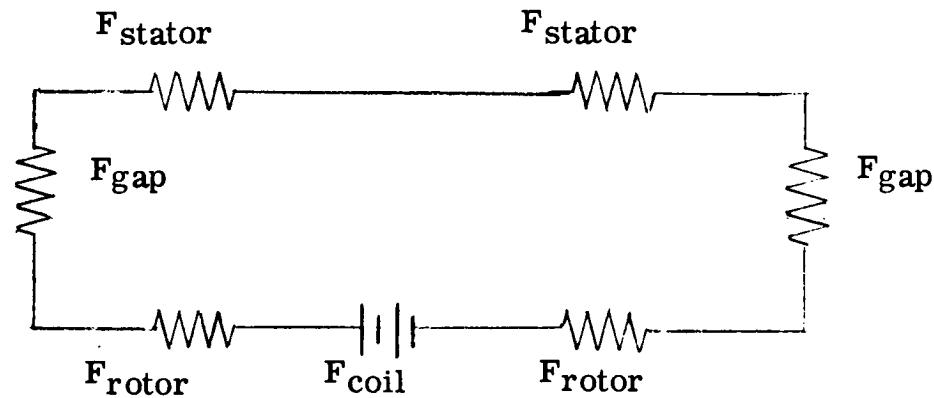
The Lundell generator with rotating coil is the generator used for years on automobiles, trucks and busses. To make this generator brushless, an exciter and rotating rectifier must be used. It is a basic generator design and for that reason it is included in the study.

Except for a difference in rotor leakage permeances, calculations for the rotating coil Lundell are similar to those of the wound-pole salient-pole generator.

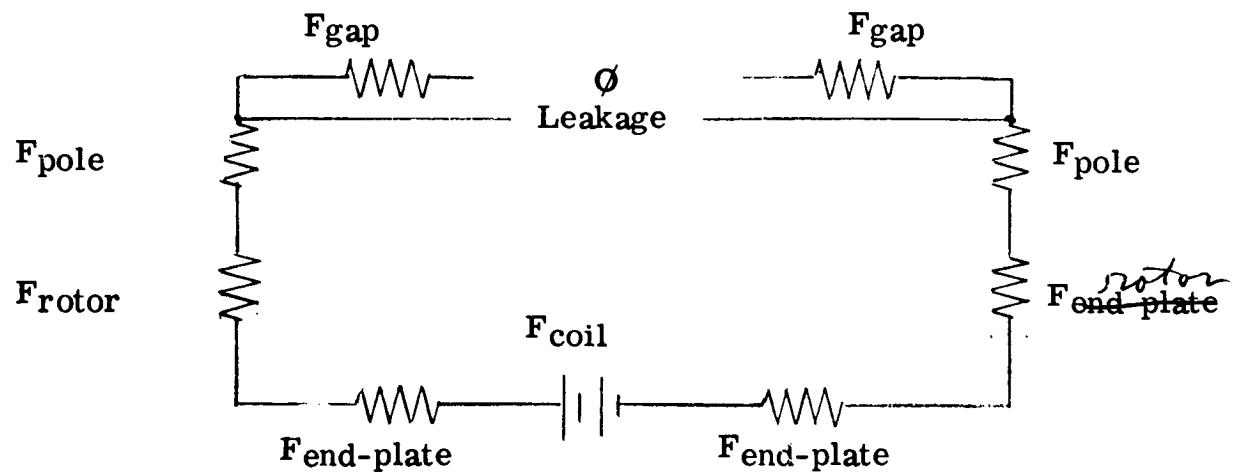
LUNDELL GENERATOR



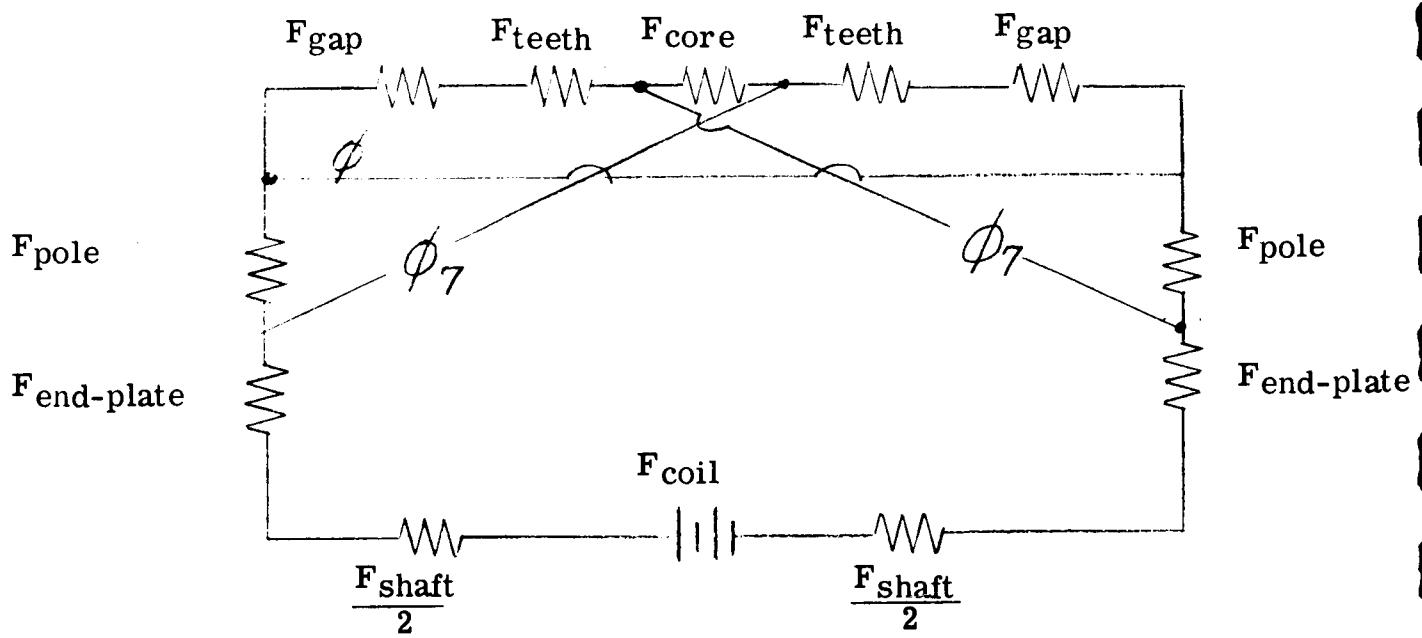
The flux circuit of the inside rotating coil Lundell A.C. generators look like this:

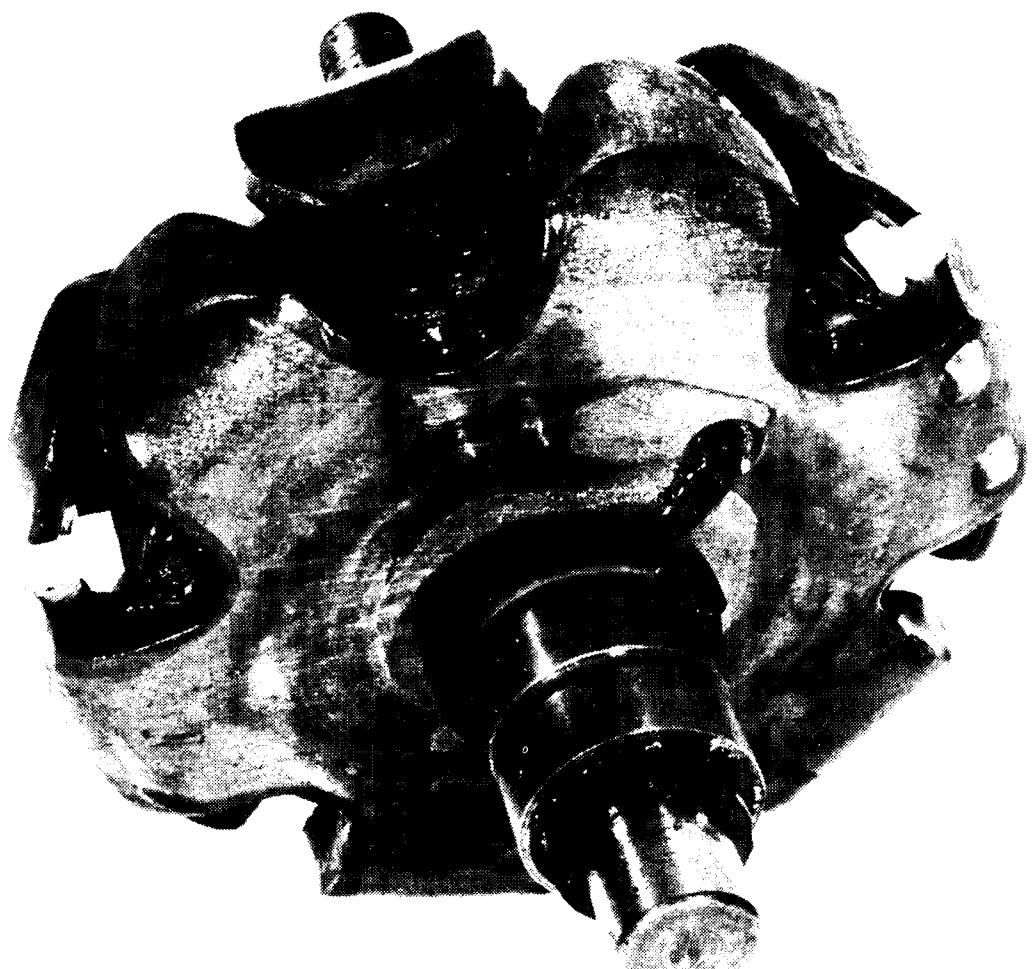


The rotor flux circuit mmf drops and leakage flux looks like this:

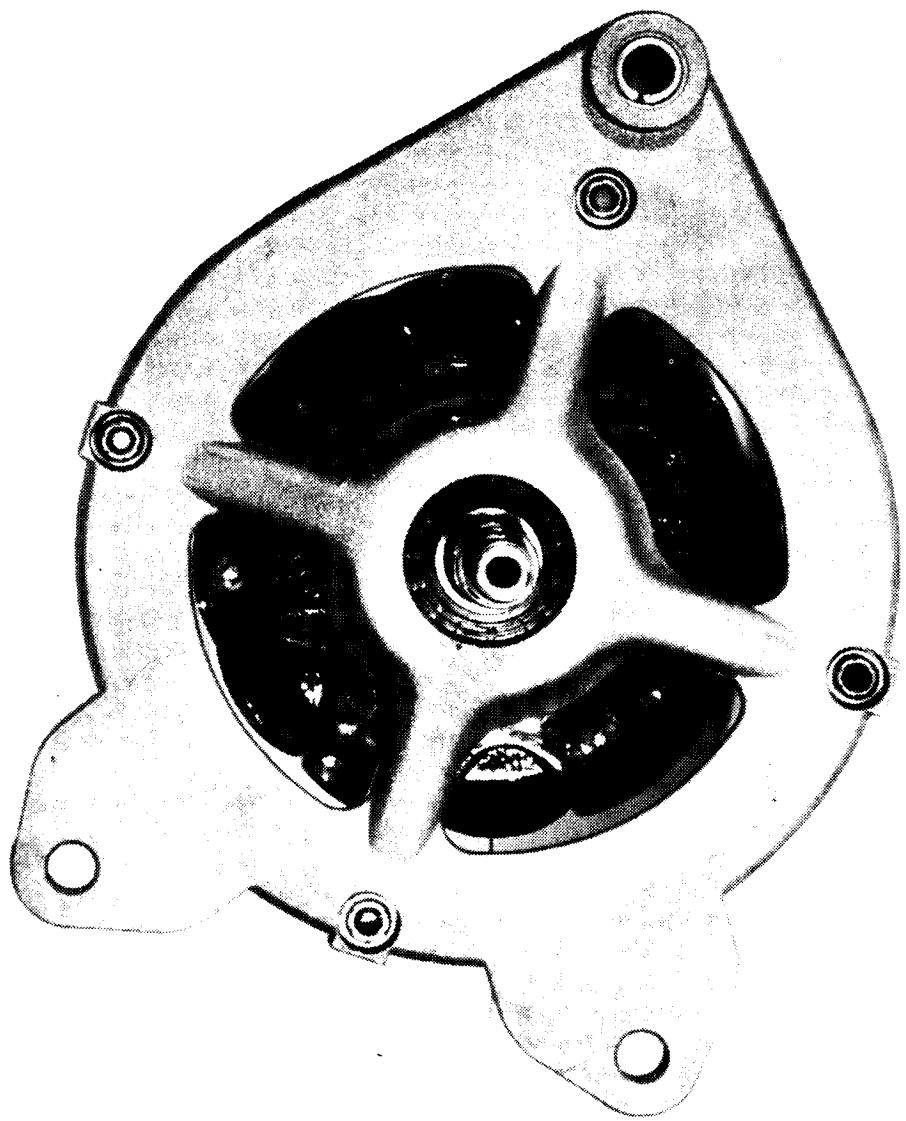
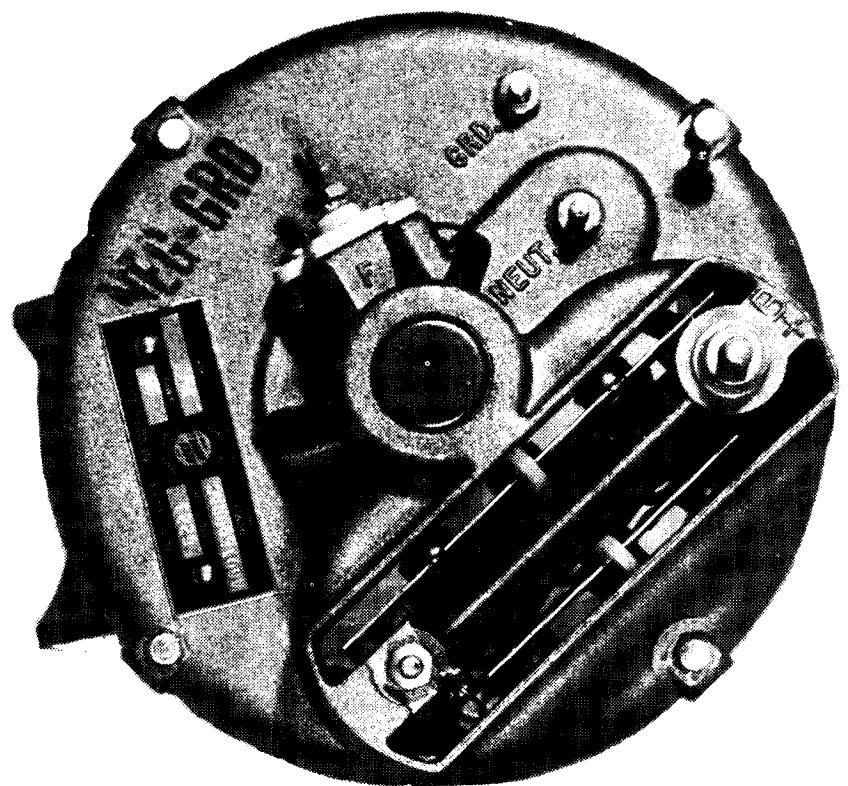


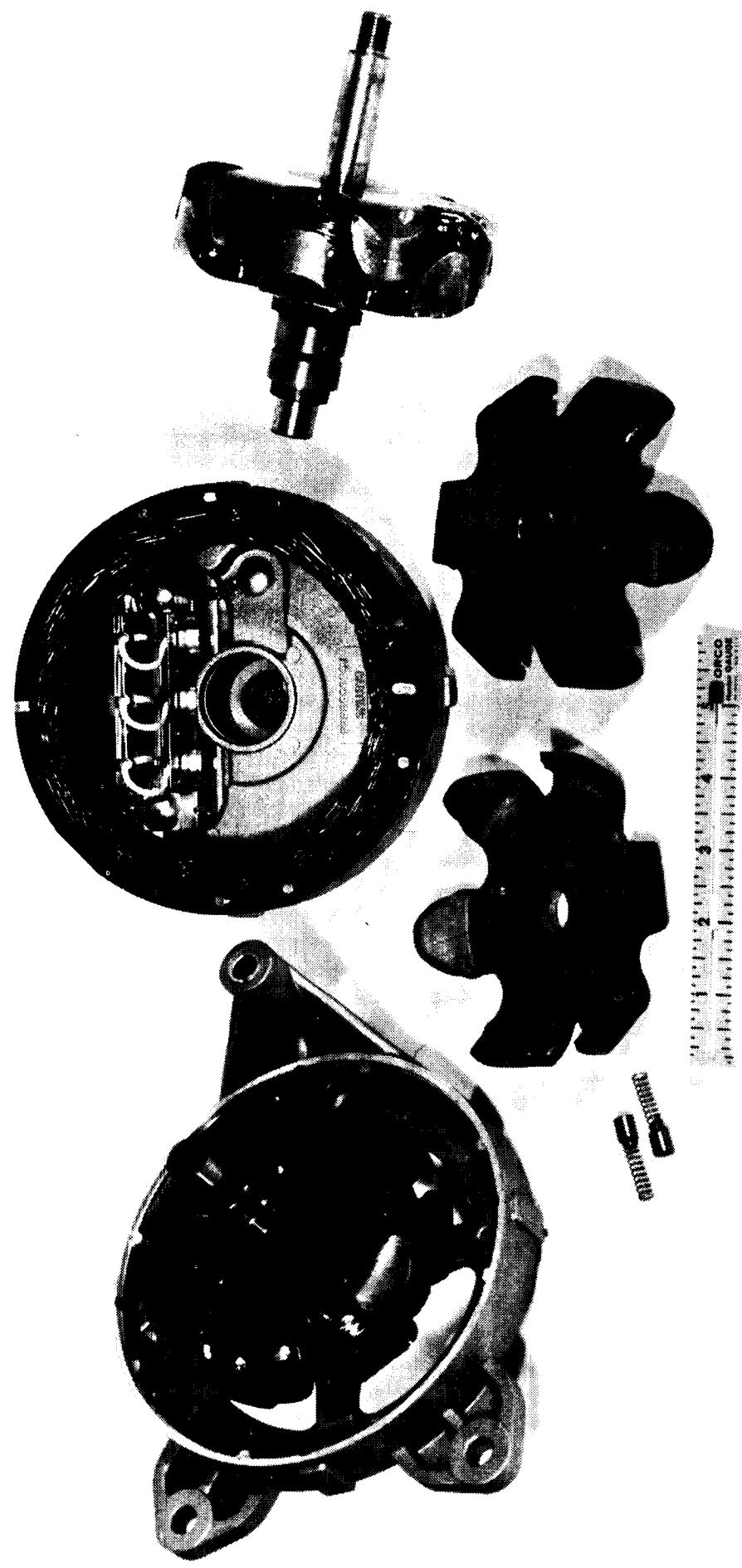
And for the entire machine, the flux circuit looks like this:





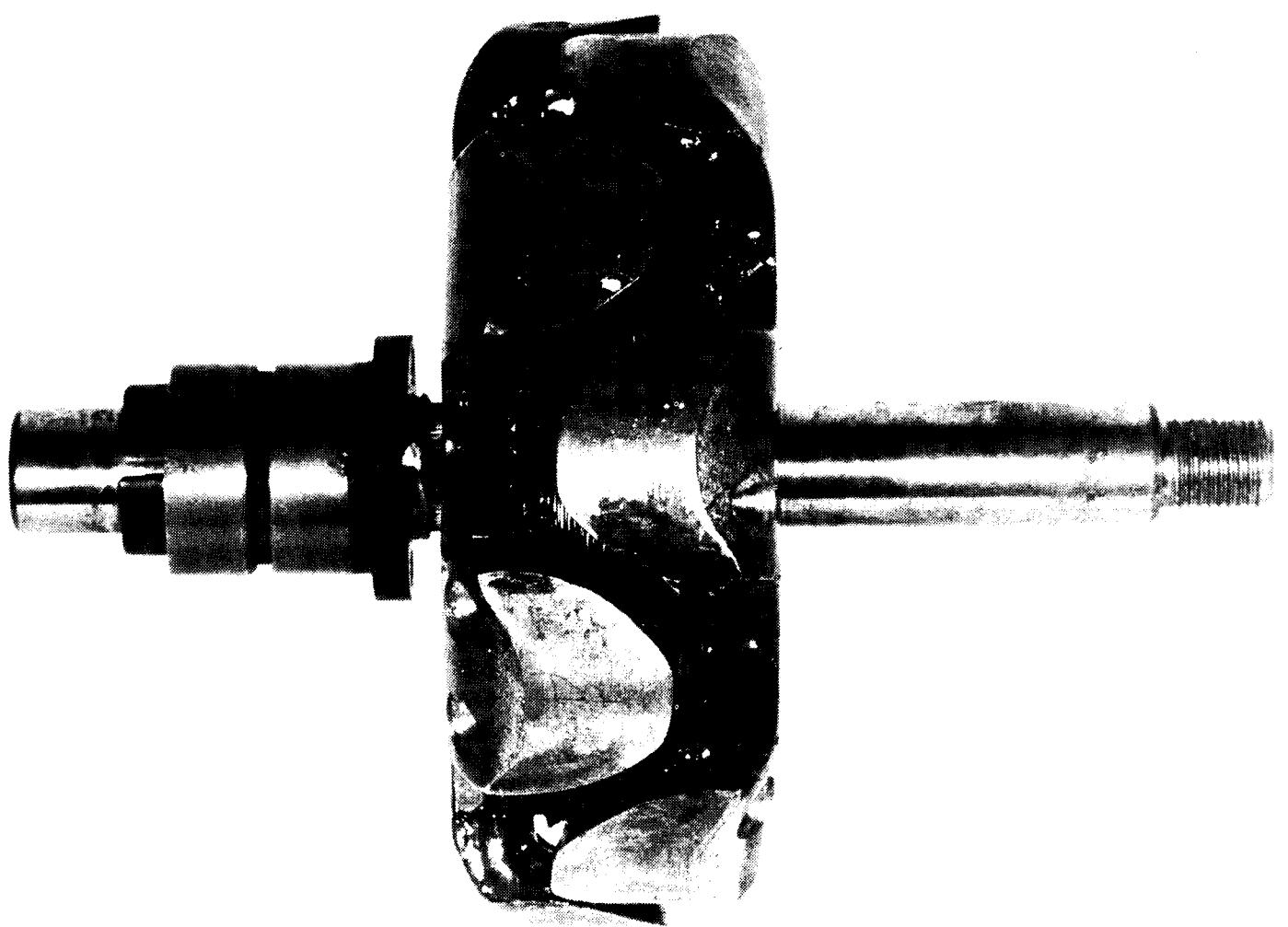
1 2 3 4 5 ORCO
Hondie GAUGE





1. Flywheel
2. Clutch plate
3. Clutch hub
4. Clutch cover
5. Clutch lever
6. Lever return spring
7. Lever stop
8. Lever stop bolt
9. Lever stop lock washer
10. Lever stop lock nut
11. Lever stop lock washer
12. Lever stop lock nut

ONCO



1 2 3 4 5 ORCO
Hondree GAUGE

The design manual has been arranged as a computer program and the sequence of calculations results from storage limitations of the smaller computers (1620).

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Following the design equations, the Fortran program is published with the same identifying equation numbers found in the design manual.

COMPUTER DESIGN - - - - - (INPUT)

MODEL

EWO

DESIGN NO(1)

PARAMETERS	CONSTANTS			POLE AND ROTOR
(2) KVA	GENERATOR KVA	.153	0.0	RATIO MAX TO MIN OF FUND
(3) E	LINE VOLTS	10.5	0.0	WINDING CONSTANT
(4) E _{ph}	PHASE VOLTS	6.0	0.0	POLE CONSTANT
(5) m	PHASES	3.0	0.0	END EXTENSION ONE TURN
(5a) f	FREQUENCY	120.0	0.0	DEMAGNETIZATION FACTOR
(6) p	POLES	12.	.7	CROSS MAGNETIZING FACTOR
(7) RPM	RPM	1200	.76	POLE EMBRACE
(8) I _{ph}	PHASE CURRENT	8.5	.5	WIDTH OF POLE (NARROW END)
(9) PF	POWER FACTOR	.9	1.4	WIDTH OF POLE (WIDE END)
(9a) K _c	ADJ. FACTOR	1.0	.1	POLE THICKNESS (NARROW END)
(10)	OPTIONAL LOAD POINT	0.0	.25	POLE THICKNESS (WIDE END)
(11) d	STATOR I.D.	4.8	.4	POLE LENGTH
(12) D	STATOR O.D.	6.64	4.76	ROTOR DIAMETER
(13) l	GROSS CORE LENGTH	4.0	0.0	WEIGHT OF ROTOR IRON
(14) n _y	NO. OF DUCTS	0.0	1.7	POLE FACE LOSS FACTOR
(15) b _y	WIDTH OF DUCT	0.0	.38	FLUX PLATE THICKNESS
(16) K _i	STACKING FACTOR (STATOR)	.98	3.2	FLUX PLATE DIAMETER
(19) k	WATTS/LB.	15.	1.88	SHAFT O.D. (FLUX CARRYING PORT.)
(20) B	DENSITY	77.4	1.3	SHAFT LENGTH (FLUX CARRYING PORT.)
(21)	TYPE OF SLOT	3.0	0.0	PERM OF LEAKAGE PATH 1
(22) b _o	SLOT OPENING	.1	0.0	PERM OF LEAKAGE PATH 2
(22) b ₁	SLOT WIDTH TOP	.16	0.0	PERM OF LEAKAGE PATH 3
(22) b ₂		.16	0.0	PERM OF LEAKAGE PATH 4
(22) b ₃		.25	0.0	PERM OF LEAKAGE PATH 5
(22) b _s	SLOT WIDTH	.205	0.0	PERM OF LEAKAGE PATH 7
(22) h _o		.015	3.8	OUTSIDE DIAMETER OF FLD COIL
(22) h ₁		.52	1.0	LENGTH OF FIELD COIL
(22) h ₂		0.0	540	NO. OF FIELD TURNS / COIL
(22) h ₃		0.0	8.8	MEAN LENGTH OF FLD. TURN
(22) h _s	SLOT DEPTH	.55	.0317	FLD. COND. DIA. OR WIDTH
(22) h _t		.015	0.0	FLD. COND. THICKNESS
(22) h _w		0.0	22	FLD. TEMP IN °C
(23) Q	NO. OF SLOTS	36.0	.69	RESISTIVITY OF FIELD COND @20°
(28)	TYPE OF WDG.	1.0	1.0	NO LOAD SAT.
(29)	TYPE OF COIL	0.0	0.0	FRICITION & WINDAGE
(30) n _s	CONDUCTORS/SLOT	10.0	Curve 12	STATOR LAM MATERIAL
(31) y	SLOTS SPANNED	3.0	Curve 15	POLE MATERIAL
(32) c	PARALLEL CIRCUITS	1.0	Curve 15	YODE MATERIAL
(33)	STRAND DIA. OR WIDTH	.0508		SHAFT MATERIAL
(34) N _{st}	STRANDS/CONDUCTOR IN DEPTH	1.0		
(34a) N' _{st}	STRANDS/CONDUCTOR	1.0		
(39)	STATOR STRAND T'KNS.	0.0		
(35) d _b	DIA. OF PIN	.25		
(36) l _{e2}	COIL EXT. STR. PORT	.25		
(37) h _{st}	UNINS. STRD. HT.	0.0		
(38) h' _{st}	DIST. BTWN. C.L OF STD.	0.0		
(42a)	PHASE BELT ANGLE	60.0		
(40) T _{sk}	STATOR SLOT SKEW	0.0		
(50) X °C	STATOR TEMP °C	22.0		
(51) ρ _s	RES'TVY STA. COND. @ 20°C	.69		
(59) δ	MAIN GAP	.670		

STATOR SLOT

DAMPER SLOT

POLE

REMARKS

KOTATING COIL LUNDELL
SUMMARY OF DESIGN CALCULATIONS ----- (OUTPUT)

MODEL NO.	EWO	DESIGN NO.	
(17) (l_s) SOLID CORE LENGTH	.39200	1.17058	CARTER COEFFICIENT (67) (K_s)
(24) (h_c) DEPTH BELOW SLOT	.37000	.02341	EFFECTIVE AIR GAP (69) (g_e)
(26) (T_s) SLOT PITCH	.41893	1.18089	RATIO MAX TO FUND. (71) (C_1)
(27) ($T_{s1/3}$) SLOT PITCH 1/3 DIST. UP	.45095	.48701	WINDING CONST. (72) (C_w)
(42) (K_{sk}) SKEW FACTOR	1.00000	.78620	POLE CONST. (73) (C_p)
(43) (K_d) DIST. FACTOR	1.00000	2.88137	END. EXT. ONE TURN (48) (L_E)
(44) (K_p) PITCH FACTOR	.99999	.82601	DEMAGNETIZING FACTOR (74) (C_M)
(45) (n_e) EFF. CONDUCTORS	359.99999	.70000	CROSS MAGNETIZING FCTR (75) (C_q)
(46) (A_c) COND. AREA	.00202	202.89000	AMP COND/IN (128) (A)
(47) (S_s) CURRENT DENSITY (STA.)	4195.80000	.24469	REACTANCE FACTOR (129) (X)
(49) (l_t) 1/2 MEAN TURN	3.28130	9.51153	LEAKAGE REACTANCE (130) (X_L)
(53) (R_{ph}) COLD STA. RES. @20°C	.13411	26.01639	REACTANCE DIRECT AXIS (131) (X_{ad})
(54) (R_{ph}) HOT STA. RES. @ X°C	.13553	18.67168	REACTANCE QUAD AXIS (132) (X_{aq})
(55) (EF_{top}) EDDY FACTOR TOP	1.00000	35.52793	SYN REACT DIRECT AXIS (133) (X_d)
(56) (EF_{bot}) EDDY FACTOR BOT	1.00000	28.18322	SYN REACT QUAD AXIS (134) (X_q)
(62) (A_t) STATOR COND. PERM.	15.81900	12.90321	FIELD LEAKAGE REACT (160) (X_f)
(63) (λ_e) END PERM.	23.05200	.28314	FIELD SELF INDUCTANCE (161) (L_f)
(65) () WT. OF STA COPPER	.76815	22.41474	UNSAT. TRANS. REACT (166) (X'_{du})
(66) () WT. OF STA IRON	1.39040	19.72497	SAT. TRANS. REACT (167) (X'_d)
(41) (V_F) POLE PITCH	1.25680	23.95410	NEG SEQUENCE REACT (170) (X_2)
(157) (-) WT OF ROTOR IRON	.00000	7.21107	ZERO SEQUENCE REACT (172) (X_0)
(145) (V_B) PERIPHERAL SPEED	1495.40150	.06812	OPEN CIR. TIME CONST. (176) (T_{dc})
(153) (B_{cf}) FLD COND. AREA	.00078	.00167	ARM TIME CONST. (177) (T_a)
(154) (R_{fL}) COLD FLD RES. @ 20°C	4.15650	.03782	TRANS TIME CONST. (178) ($T'd$)
(155) (R_f) HOT FLD RES. @ X°C	4.20060	.00500	SUB TRAN TIME CONST. (179) ($T''d$)
(156) (-) WT OF FLD COPPER	1.20320	299.45459	TOTAL FLUX (90) (Φ_T)
(80) (P_1) PERM OF LEAKAGE PATH 1	.13720	19.61926	FLUX PER POLE (93) (Φ_P)
(81) (P_2) PERM OF LEAKAGE PATH 2	.72783	49.64538	GAP DENSITY (MAIN) (95) (B_g)
(82) (P_3) PERM OF LEAKAGE PATH 3	.42356	80.11422	TOOTH DENSITY (91) (B_t)
(83) (P_4) PERM OF LEAKAGE PATH 4	.80140	67.63398	CORE DENSITY (94) (B_c)
(84) (P_5) PERM OF LEAKAGE PATH 5	18.19800	5.92965	TOOTH AMPERE TURNS (97) (F_t)
(85) (P_7) PERM OF LEAKAGE PATH 7	34.60700	2.27248	CORE AMPERE TURNS (98) (F_c)
(159) (SC) SHORT CIR NI	12944.00000	364.34000	GAP AMPERE TURNS (MAIN) (96) (F_g)
(159) (SC) SHORT AIR RATIO	.06201		

PERCENT LOAD	0	100	150	200	OPTION
(ϕ_2) (100) LEAKAGE FLUX	1.122	(ϕ_{99}) (196)	19.458	21.397	23.514
(ϕ_{PT}) (102) TOTAL FLUX/POLE	35.741	(ϕ_{PL}) (213)	39.980	42.378	44.987
(B_P) (103) POLE DENSITY	102.110	(B_{PL}) (213)	114.230	121.080	128.530
(B_{SH}) (113) SHAFT DENSITY	82.070	(B_{SHL}) (232)	92.272	98.072	104.430
(F_{NL}) (127) TOTAL NI	802.760	(F_{FL}) (236)	975.870	1079.900	1202.100
(I_{ENL}) (127c) FIELD AMPERES	1.486	(I_{EFL}) (237)	1.807	1.999	2.226
(S_F) (127c) CUR. DEN. FLD.	1884.500	(S_F) (239)	2290.900	2535.100	2822.100
(E_{FNL}) (127b) FIELD VOLTS	6.179	(E_{FFL}) (238)	7.591	8.400	9.351
(W_C) (185) STA CORE LOSS	14.790	(W_C) (185)	14.790	14.790	14.790
(W_{TFL}) (184) STA TOOTH LOSS	14.966	(W_{TFL}) (242)	15.241	15.585	16.067
(I^2R_S) (194) STATOR CU LOSS	.000	(I^2R_S) (245)	29.376	44.064	58.752
(-) (195) EDDY LOSS	.000	(-) (246)	.000	.000	.000
(W_{PFL}) (186) POLE FACE LOSS	4.209	(W_{PFL}) (243)	4.443	4.737	5.148
(I^2R_F) (182) FIELD COIL LOSS	9.184	(I^2R_F) (241)	13.717	16.799	20.818
(F_{sw}) (183) FSW LOSS	2.071	(F_{sw}) (183)	2.071	2.071	2.071
(-) (196) TOTAL LOSSES	45.221	(-) (247)	79.640	98.047	117.647
(-) (--) PERCENT EFF	.000	(-) (251)	63.356	67.810	70.067

ROTATING COIL LUNDELL
NO LOAD SATURATION OUTPUT SHEET

ITEMS VOLTS	(3)(E) VOLTS	(91) B_t STA. TOOTH DENSITY	(97) F_t STATOR TOOTH NI	(94) B_c STA. CORE DENSITY	(98) F_c STA. CORE N.I.	(96) F_g GAP NI.
	(100) \emptyset_L LEAKAGE FLUX	(102) \emptyset_{PT} TOTAL FLUX/POLE	(103) B_p POLE DENSITY	(104) F_p POLE N.I.	(113) B_{SH} SHAFT DENSITY	(127) F_{NL} TOTAL NI.
80%	8.40000 12.78488	64.09120 28.48008	2.61187 81.37167	54.10640 9.15131	1.32916 65.35558	291.47200 632.70592
90%	9.45000 14.42447	72.10260 32.08157	3.69744 91.66163	60.86970 11.09352	1.69459 73.63658	327.90600 715.36887
100%	10.50000 16.12287	80.11400 35.74187	5.92965 102.11965	67.63300 13.81693	2.27247 82.07139	364.34000 802.76323
110%	11.55000 17.96178	88.12540 39.54268	11.21135 112.97910	74.39630 19.28361	3.04741 90.88458	400.77400 904.10335
120%	12.60000 20.40666	96.13680 43.94946	29.56791 125.56989	81.15960 29.02051	4.74919 101.23533	437.20800 1045.17030
130%	13.65000 23.88673	104.14820 49.39143	70.11762 141.11838	87.92290 74.88013	8.17752 114.57216	473.64200 1319.53710
140%	MACHINE SATURATED					
150%						
160%						

INPUT PARAMETERS 1

.153	10.5	6.	3.	120.	12.	1200.	8.5	.9	1.
0.	4.8	6.64	.4			.98	15.	77.4	3.
.1	.16	.16	.25	.205	.015	.52			.55
.015		36.	1.		10.	3.	1.	.0508	1.
1.	0.	.25	.25			60.		22.	.69
.020						.7	.76	.5	1.4
.1	.25	.4	4.76		1.7	.38	3.2	1.88	1.3
						3.8	1.	540.	8.8
.0317		22.	.69	1.					

SATURATION CURVE VALUES (STATOR MATERIAL)

140.	10.	1.	38.	1.9	59.
3.8	75.	7.6	86.	16.	93.
35.	100.	90.	107.	160.	118.
230.	140.	950.			

SATURATION CURVE VALUES (POLE MATERIAL)

150.		3.	34.	10.	57.
16.	85.	24.	103.	35.	125.
70.	137.	130.	145.	260.	148.
600.	150.	1500.			

SATURATION CURVE VALUES (YODE MATERIAL)

150.	0.	3.	34.	10.	57.
16.	85.	24.	103.	35.	125.
70.	137.	130.	145.	260.	148.
600.	150.	1500.			

INSIDE-COIL, ROTATING-COIL, LUNDELL, A. C. GENERATOR

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
<u>A, a</u>			
(128)	A	A	Ampere conductors per inch
(46)	a_c	AC	Conductor area of stator winding
(79)	a_p	AP	Pole area
<u>B, b</u>			
(20)	B	BK	Density
(22)	b_o	BO	Width of stator slot opening
(94)	B_c ,	BC1	Stator core density N. L.
(95)	B_g ,	BG1	Main air gap density (N. L.)
(76)	b_{p1}	BP1	Width of pole at end of stator stack
(76)	b_{p2}	BP2	Width of pole at end of stator stack
(103)	B_p	BP	Pole density
(113b)	B_{pl}	BPL	Pole density under load
(22)	b_s	BS	Stator slot dimension per Fig. 1
(113)	B_{SH}	BSH	Shaft density
(232)	B_{SHL}	B_{SHL}	Shaft flux density under load
(57a)	$b_t \frac{1}{3}$	SM	Stator tooth width 1/3 distance from narrowest end
(91)	B_T ,	BT1	Stator tooth density (N.L.)
(57)	b_{tm}	TM	Stator tooth width 1/2 distance from narrowest end

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation
(15)	b_v	BV	Radial duct width
		<u>C, c</u>	
(32)	c	C	Parallel paths
(71)	C_1	C1	Ratio of maximum fundamental of field form to the actual maximum of the field form
(74)	C_M	CM	Demagnetizing factor
(73)	C_P	CP	Pole constant
(75)	C_q	CQ	Cross magnetizing factor
(72)	C_W	CW	Winding constant
		<u>D, d</u>	
(12)	D	DU	Stator lamination outside diameter
(11)	d	DI	Stator lamination inside diameter
(35)	d_b	DB	Diameter of bender pin
(78)	d_{fp}	DFP	Diameter of flux plate
(78)	d_{oc}	DC1	Outside diameter of coil
(11a)	d_r	DR	Outside rotor diameter
(78)	d_s	DS1	Outside diameter of shaft

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
<u>E, e</u>			
(3)	E	EE	Line volts
(55)	E_F_{TOP}	ET	Eddy factor top
(56)	E_F_{BOT}	EB	Eddy factor bottom
(238)	E_{FFL}	EPFL	Full load field volts
(127b)	E_{FNL}	EPNL	No load field volts
(4)	E_{PH}	EP	Phase volts
<u>F, f</u>			
(5a)	f	F	Frequency
(98)	F_c	FC	N. L. stator core ampere turns
(236)	F_{FL}	FFL	Total full load ampere turns
(96)	F_g	FG	N. L. main gap ampere turns
(127)	F_{NL}	FNL	Total no load ampere turns
(104)	F_p	FP	Pole ampere turns
(98a)	F_s	FS	Stator ampere turns
(180)	F_{SC}	FSC	Short circuit ampere turns
(233)	F_{SHL}	FSHL	Ampere turn drop in shaft under load
(97)	F_T	FT	N. L. stator tooth ampere turns
(183)	F & W	WF	Friction and windage

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
<u>G, g</u>			
(59)	g	GC	Main air gap
(69)	g_e	GE	Effective main gap
<u>H, h</u>			
(24)	h_c	HC	Depth below slot
(38)	h_{ST}	SD	Distance between center line of strand in depth
(39)	h_{ST}	SH	Stator coil strand thickness (largest dimension)
<u>I, i</u>			
(237)	I_{FFL}	AIFL	F. L. field current
(127a)	I_{FNL}	AINL	N. L. field current
(8)	I_{PH}	PI	Phase current
(182)	$I^2 R_F$	FEL	N. L. field coil loss
(241)	$I^2 R_{FL}$	FCUL	F. L. coil copper loss
(194)	$I^2 R$	PS	N. L. stator copper loss
(245)	$I^2 R_L$	SCUL	F. L. stator copper loss
<u>K, k</u>			
(19)	k	WL	Watts/lb core loss
(9a)	K_c	CK	Adjustment factor
(43)	K_d	DF	Distribution factor

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation
(63)	K_e	EK	Leakage reactive factor
(16)	K_i	SF	Stacking factor
(44)	K_p	CF	Pitch factor
(67)	K_s	CC	Carter coefficient
(42)	K_{SK}	FS	Skew factor
(2)	K_{VA}	VA	Generator rating
(61)	K_X	FF	Factor to account for difference in phase current in coil sides in same slot

L, l

(13)	ℓ	CL	Gross core length (stator)
(76)	ℓ_{co}	ALCO	Length of coil
(48)	L_E	EL	Stator coil end extension length
(36)	ℓ_{e2}	CE	Coil extension beyond core
(161)	L_F	SI	Field inductance
(76)	ℓ_p	ALP	Length of pole
(17)	ℓ_s	SS	Solid core length
(78)	ℓ_{SH}	ALSH	Effective length of shaft
(49)	ℓ_t	HM	1/2 mean turn (stator coil)
(147)	ℓ_{tf}	FE	1/2 mean turn of field coil

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
<u>M, m</u>			
(5)	m	PN	No. of phases
<u>N, n</u>			
(146)	N_F	PT	Field turns per coil
(45)	n_e	EC	Effective conductors
(30)	n_s	SC	Conductors per slot
(34)	N_{ST}	SN	Strands per conductor in depth
(34a)	N'_ST	SN1	Strands per conductor (total)
(14)	n_v	HV	Radial ducts
<u>P, p</u>			
(6)	p	PX	No. of poles
(9)	PF	PF	Power factor
(80)	P_1	P1	Pole head end leakage permeance
(81)	P_2	P2	Pole head side leakage permeance
(82)	P_3	P3	Pole body end leakage permeance
(83)	P_4	P4	Pole body side leakage permeance
(84)	P_5	P5	Field coil leakage permeance
(86)	P_7	P7	Stator core to coil yoke leakage permeance

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
<u>Q, q</u>			
(23)	Q	QQ	No. of slots
(25)	q	QN	Slots per pole per phase
<u>R, r</u>			
(154)	$R_f(\text{cold})$	FK	Cold field resistance at 20 °C
(155)	$R_f(\text{hot})$	FR	Hot field resistance at X °C
(7)	RPM	RPM	Revolutions per minute
(53)	$R_{\text{SPH}}(\text{cold})$	RG	Stator resistance per phase at 20 °C
(54)	$R_{\text{SPH}}(\text{hot})$	RP	Stator resistance per phase at X °C
<u>S, s</u>			
(181)	SCR	SCR	Short circuit ratio
(127c)	s_F	CD	Current density in field conductor
(47)	s_S	S	Current density in stator conductor
<u>T, t</u>			
(177)	T_a	TA	Armature time constant
(178)	T_d'	T5	Transient time constant
(176)	T_{do}	TC	Open circuit time constant
(178a)	T_d''	T4	Subtransient time constant
(78)	t_{fp}	TFP	Thickness of flux plate
(76)	t_{p1}	TP1	Thickness of pole at end of stator
(76)	t_{p2}	TP2	Thickness of pole at end of stator

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
<u>V, v</u>			
(145)	v_r	VR	Peripheral speed
<u>W, w</u>			
(185)	w_C	WQ	Stator core loss
(186)	w_{NPL}	WN	N. L. pole face loss
(243)	w_{PFL}	WNL	F. L. pole face loss
(242)	w_{TFL}	WTFL	F. L. stator teeth loss
(184)	w_{TNL}	WT	N. L. stator teeth loss
<u>X, x</u>			
(129)	X	XR	Reactance factor
(131)	x_{ad}	XD	Reactance direct axis
(132)	x_{aq}	XQ	Reactance quadrature axis
(167)	x_d'	XS	Saturated transient reactance
(133)	x_d	XA	SYNCHRONOUS REACTANCE - DIRECT AXIS
(166)	x_{du}'	XU	Unsaturated transient reactance
(160)	x_F	XF	Effective field leakage reactance
(150)	x_f °C	T2	Expected field temperature at full load
(130)	x_ℓ	XL	Leakage reactance
(134)	x_q	XB	Synchronous reactance quadrature axis

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
(50)	X_s °C	TI	Stator expected temperature at F.L.
(170)	X_2	XN	Negative sequence reactance
(172)	X_0	XO	Zero sequence reactance

Y, y

(31)	y	YY	Throw or coil span
------	---	----	--------------------

(207)	ϕ_{7L}	PL7	F.L. leakage flux in Path 7
(92)	ϕ_p	FQ	Flux per pole N.L.
(213)	ϕ_{PL}	FQL	Flux per pole F.L.
(88)	ϕ_T	TG	Total flux N.L.

γ

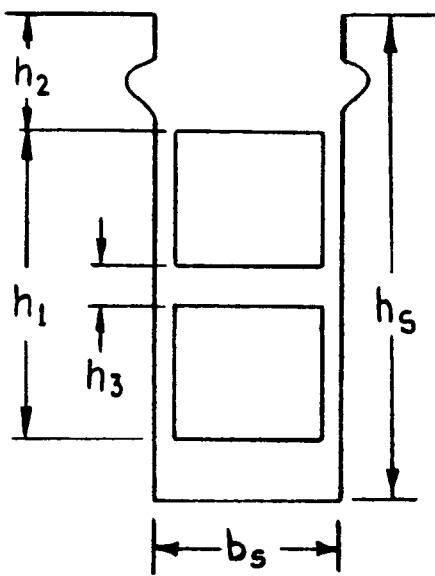
(41)	γ_p	TP	Pole pitch
(26)	γ_s	TS	Stator slot pitch
(40)	γ_{SK}	SK	Stator slot skew
(27)	$\gamma_{S\ 1/3}$	TT	Stator slot pitch 1/3 distance from narrowest section of tooth

λ

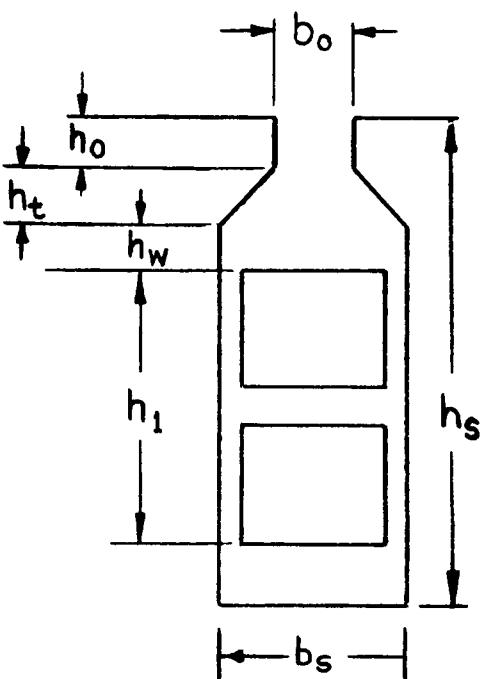
(64)	λ_E	EW	End winding permeance
(160c)	λ_F	FL	Rotor leakage permeance

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
	<u>ρ</u>		
(151)	ρ_f	RR	Resistivity of field conductor at 20 °C
(152)	ρ_f (hot)		Resistivity of field conductor at expected temperature at F.L.
(51)	ρ_s	RS	Resistivity of stator winding at 20 °C

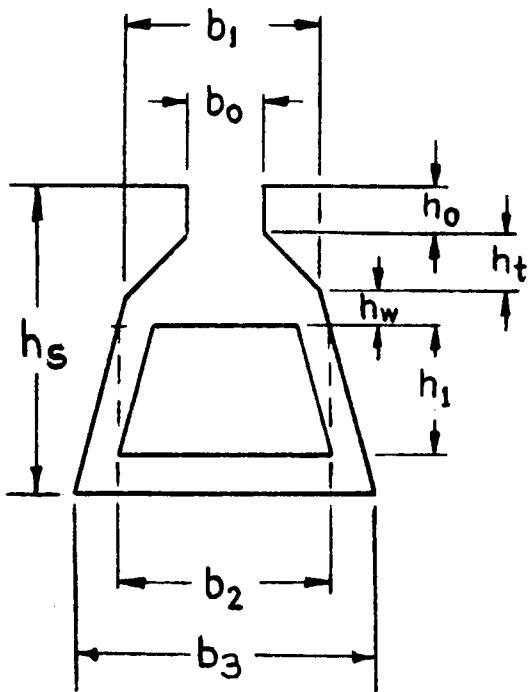
(a) Open Slots



(b) Constant Slot Width



(c) Constant Tooth Width



(d) Round Slots

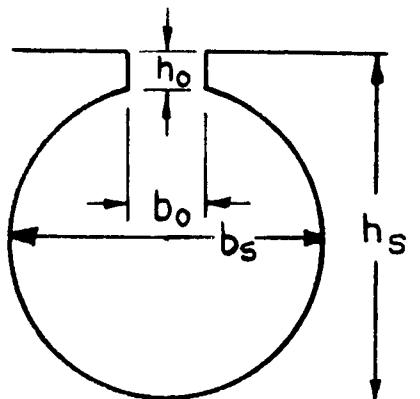


FIG 1

TABLE - 1

$\frac{g_i}{g_j}$	$\frac{y_i}{y_j}$ For Harmonics At Different Pitches											
	$\frac{y_i}{y_{j_1}}$											
	$\frac{y_i}{y_{j_2}}$											
	$\frac{y_i}{y_{j_3}}$											
	$\frac{y_i}{y_{j_4}}$	$\frac{y_i}{y_{j_5}}$	$\frac{y_i}{y_{j_6}}$	$\frac{y_i}{y_{j_7}}$	$\frac{y_i}{y_{j_8}}$	$\frac{y_i}{y_{j_9}}$	$\frac{y_i}{y_{j_{10}}}$	$\frac{y_i}{y_{j_{11}}}$	$\frac{y_i}{y_{j_{12}}}$	$\frac{y_i}{y_{j_{13}}}$	$\frac{y_i}{y_{j_{14}}}$	$\frac{y_i}{y_{j_{15}}}$
1	3/3											
2	6/6											
3	9/9	8/9										
4	12/12	11/12										
5	15/15	14/15										
6	18/18	17/18										
7	21/21	20/21										
8	24/24	23/24										
9	27/27	26/27										
10	30/30	29/30										
$\frac{y_i}{y_{j_6}}$	1.0	967.9	959.9	952.9	945.9	934.9	926.9	917.9	905.9	899.9	875.9	857.9
1	1.0	999.9	998.9	997.9	996.9	995.9	993.9	991.9	989.9	988.9	985.9	981.9
3	1.0	988.9	987.9	981.9	975.9	966.9	951.9	940.9	928.9	910.9	891.9	865.9
5	1.0	966.9	958.9	947.9	931.9	906.9	866.9	835.9	793.9	733.9	693.9	656.9
7	1.0	943.9	943.9	891.9	864.9	819.9	743.9	686.9	609.9	554.9	392.9	177.9
9	1.0	897.9	866.9	831.9	782.9	707.9	588.9	500.9	449.9	390.9	334.9	201.9
11	1.0	834.9	802.9	750.9	680.9	574.9	407.9	387.9	31.9	175.9	156.9	101.9
13	1.0	777.7	727.6	659.5	583.4	423.2	208.0	0.98				
15	1.0	707.7	643.6	556.4	434.4	259.0	174.0	143.0	101.0	61.0	31.0	
17	1.0	629.7	558.0	444.2	295.6	208.7	108.6	39.6	30.6	1.0		
19	1.0	545.4	444.3	321.1	149.9	0.87	407.5	597.7	783.7	956.7	988.7	981.7
21	1.0	454.0	342.0	195.0	259.0	588.6	624.0	788.6	866.5	909.0	933.0	961.0
23	1.0	358.8	231.0	164.9	149.4	423.7	743.0	866.9	957.0	985.0	998.0	998.0
25	1.0	291.6	166.6	79.5	205.7	574.6	911.8	186.7	342.0	195.0	500.0	321.0
27	1.0	170.0	0.0	195.4	134.4	707.9	521.0	624.0	195.0	707.0	223.0	0.0
29	1.0	0.92	116.3	321.1	563.8	951.7	973.7	365.7	782.0	894.0	968.0	999.0
31	1.0	0.58	231.4	442.7	580.9	906.9	995.9	891.9	855.9	981.9	981.9	981.9
33	1.0	156.3	312.5	552.5	782.9	966.9	951.7	766.9	434.7	287.9	177.9	72.9
35	1.0	259.0	449.9	659.6	966.9	946.6	597.1	300.0	0.0	287.6	717.0	105.0
37	1.0	358.6	536.7	931.1	996.7	743.7	746.3	191.9	895.5	556.0	383.3	105.0
39	1.0	454.0	613.7	831.9	975.9	696.9	583.7	363.7	145.7	309.7	777.7	145.7
41	1.0	345.7	727.7	971.7	997.7	906.7	407.7	609.7	899.7	984.7	996.7	996.7
43	1.0	629.7	802.4	947.7	997.7	819.7	208.7	271.7	793.7	899.7	981.7	981.7
45	1.0	707.7	846.9	987.7	925.7	707.0	0.0	500.9	924.7	107.0	222.7	145.7
47	1.0	777.7	918.9	998.9	931.1	574.7	208.7	636.7	981.7	107.0	222.7	145.7
49	1.0	839.8	938.9	998.6	866.6	423.4	407.8	835.9	981.7	906.7	988.7	981.7
51	1.0	891.9	985.9	981.9	782.9	254.7	588.9	940.7	323.7	156.7	707.0	223.7
53	1.0	914.9	998.9	831.1	442.7	495.7	835.9	985.7	755.7	889.7	981.7	981.7
55	1.0	966.9	998.9	897.9	563.7	605.7	365.7	707.9	985.7	933.7	988.7	981.7
57	1.0	998.9	981.9	831.1	434.7	255.7	931.9	490.7	383.7	624.7	981.7	981.7
59	1.0	999.9	958.7	756.2	295.7	423.4	985.7	835.7	311.7	826.9	988.7	981.7
61	1.0	999.9	978.9	659.1	149.9	514.7	949.9	866.6	449.7	978.9	981.7	981.7
63	1.0	988.9	846.5	556.0	0.0	707.5	500.0	809.0	0.0	891.0	866.7	866.7
65	1.0	946.8	802.4	442.8	149.9	814.7	864.7	271.6	609.1	975.7	981.7	981.7

VALUES OF K_{dn} FOR INTEGRAL-SLOT, 30 WINDINGS - TABLE 2

n	K_{dn} - HARMONIC DISTRIBUTION FACTORS										
$q =$	2	3	4	5	6	7	8	9	10	∞	
1	.966	.960	.958	.957	.957	.957	.956	.955	.955	.955	
3	.707	.667	.654	.646	.644	.642	.641	.640	.639	.636	
5	.259	.217	.205	.200	.197	.195	.194	.194	.193	.191	
7	-.259	-.177	-.158	-.149	-.145	-.143	-.141	-.140	-.140	-.136	
9	-.707	-.333	-.270	-.247	-.236	-.229	-.225	-.222	-.220	-.212	
11	-.966	-.177	-.126	-.110	-.102	-.097	-.095	-.093	-.092	-.087	
13	-.966	.217	.126	.102	.092	.086	.083	.081	.079	.073	
15	-.707	.667	.270	.200	.172	.158	.150	.145	.141	.127	
17	-.259	.960	.158	.102	.084	.075	.070	.066	.064	.056	
19	.259	.960	-.205	-.110	-.084	-.072	-.066	-.062	-.060	-.059	
21	.707	.667	-.654	-.247	-.172	-.143	-.127	-.118	-.112	-.091	
23	.966	.217	-.958	-.149	-.092	-.072	-.063	-.057	-.054	-.041	
25	.966	-.177	-.958	.200	.102	.075	.063	.056	.052	.038	
27	.707	-.333	-.654	.646	.236	.158	.127	.111	.101	.071	
29	.259	-.177	-.205	.957	.145	.086	.066	.056	.050	.033	
31	-.259	.217	.158	.957	-.197	-.097	-.070	-.057	-.050	-.031	

33	-.707	.667	.270	.646	-.644	-.229	-.150	-.118	-.101	-.058
35	-.966	.960	.126	.200	-.957	-.143	-.083	-.062	-.052	-.027
37	-.966	.960	-.126	-.149	-.957	.195	.095	.066	.054	.026
39	-.707	.667	-.270	-.247	-.644	.642	.225	.145	.112	.049
41	-.259	.217	-.158	-.110	-.197	.957	.141	.081	-.060	.023
43	.259	-.177	.205	.102	.145	.957	-.194	-.093	-.064	-.022
45	.707	-.333	.654	.200	.236	.642	-.641	-.222	-.141	-.042
47	.966	-.177	.958	.102	.102	.195	-.956	-.140	-.079	-.020
49	.966	.217	.958	-.110	-.092	-.143	-.956	.194	.092	.019
51	.707	.667	.654	-.247	-.172	-.229	-.641	.640	.220	.038
53	.259	.960	.205	-.149	-.084	-.097	-.194	.955	.140	.018
55	-.259	.960	-.158	.200	.084	.086	.141	.955	-.193	-.017
57	-.707	.667	-.270	.646	.172	.158	.225	.640	-.639	-.033
59	-.966	.217	-.126	.957	.092	.075	.095	.194	-.955	-.016
61	-.966	-.177	.126	.957	-.102	-.072	-.083	-.140	-.955	.016
63	-.707	-.333	.270	.646	-.236	-.143	-.150	-.222	-.639	.030
65	-.259	-.177	.158	.200	-.145	-.072	-.070	-.093	-.193	.015

ROUND COPPER WIRE

TABLE 3

SIZE AWG	BARE DIAMETER	AREA □"	“/1000' @25°C	SINGLE FORMVAR	HEAVY FORMVAR	SINGLE GLASS FORMVAR	BARE WT. #/1000'	SINGLE GLASS SILICONE	DOUBLE GLASS SILICONE
36	.0050	.0000196	424	.0056	.0060		.0757		
35	.0056	.0000246	338	.0062	.0066		.0949		
34	.0063	.0000312	266	.0070	.0074		.1201		
33	.0071	.0000396	210	.0079	.0084		.1526		
32	.0080	.0000503	165	.0088	.0094	.0121	.1937		
31	.0089	.0000622	134	.0097	.0104	.0130	.2398		
30	.0100	.0000785	106	.0108	.0116	.0142	.3025	.0132	.0152
29	.0113	.000100	83.1	.0122	.0130	.0156	.3866	.0145	.0165
28	.0126	.000125	66.4	.0135	.0144	.0169	.4806	.0158	.0178
27	.0142	.000158	52.6	.0152	.0161	.0186	.6101	.0174	.0194
26	.0159	.000199	41.7	.0169	.0179	.0203	.7650	.0191	.0211
25	.0179	.000252	33.0	.0190	.0200	.0224	.970	.0211	.0231
24	.0201	.000317	26.2	.0213	.0223	.0263	1.223	.0251	.0276
23	.0226	.000401	20.7	.0238	.0249	.0289	1.546	.0276	.0301
22	.0254	.000507	16.4	.0266	.0277	.0317	1.937	.0303	.0328
21	.0285	.000638	13.0	.0299	.0310	.0349	2.459	.0335	.0360
20	.0320	.000804	10.3	.0334	.0346	.0384	3.099	.0370	.0395
19	.0360	.00102	8.14	.0374	.0386	.0424	3.900	.0409	.0434
18	.0403	.00126	6.59	.0418	.0431	.0468	4.914	.0453	.0478
17	.0453	.00159	5.22	.0469	.0482	.0519	6.213	.0503	.0528
16	.0508	.00204	4.07	.0524	.0538	.0575	7.812	.0558	.0583
15	.0571	.00255	3.26	.0588	.0602	.0639	9.87	.0621	.0646
14	.0641	.00322	2.58	.0659	.0673	.0710	12.44	.0691	.0716
13	.072	.00407	2.04	.0738	.0753	.0789	15.69	.0770	.0795
12	.0808	.00515	1.61	.0827	.0842	.0877	19.76	.0858	.0883
11	.0907	.00650	1.28	.0927	.0942	.0977	24.90	.0957	.0982
10	.102	.00817	1.02	.1039	.1055	.1089	31.43	.1069	.1094
9	.114	.0102	.814	.1165	.1181	.1225	39.62	.1204	.1254
8	.129	.0131	.634	.1306	.1323	.1366	49.98	.1345	.1395
7	.144	.0163	.510	.1465	.1482	.1525	63.03	.1503	.1553
6	.162	.0206	.403	.1643	.1661	.1703	79.44	.1680	.1730
5	.182	.0260	.319	.1842	.1861	.1902	100.2	.1879	.1929
4	.204	.0327	.254				126.3	.2103	.2153
3	.229	.0412	.202				159.3		
2	.258	.0523	.159				200.9		
0	.325	.0830	.100						
2/0	.365	.105	.0791						
4/0	.460	.166	.0500						

CURVE 2

From Kennard and Spooner "Surface Iron Losses with Respect
to Laminated Materials", Trans. AIEE, Vol. 43, 1924,
pp 262-281.

REFER TO ITEM (150) IN SALIENT POLE DESIGN MANUAL FOR
SAMPLE USE OF THIS CURVE

POLE FACE LOSS WATTS = $W_s = K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5 \cdot K_6 \cdot$ BORE AREA

$$K_1 = .75 \text{ FOR SOLID POLE}$$

$$= 1.0 \text{ FOR } 125 \text{ TH LOW C STEEL}$$

$$= 3.50 \text{ FOR } 125 \text{ TH LOW C STEEL}$$

$$= 1.17 \text{ FOR } 028 \text{ TH LOW C STEEL}$$

$$B_g = \text{GAP DENSITY KILOINES / SQIN}$$

$$b_s = \text{SLOT WIDTH} = b_o \text{ for partially closed slots}$$

$$G = \text{AIR GAP (ACTUAL)}$$

$$C = \text{FUNDAMENTAL OF FIELD FORM}$$

$$F_{sf} = \left(\frac{R}{60}\right) (\text{SLOTS}) = \text{SLOT FREQUENCY}$$

$$T_s = \text{slot pitch}$$

$$\text{BORE AREA} = \pi R^2 l$$

$$e =$$

$$1.5$$

$$1.0$$

$$.9$$

$$.8$$

$$.7$$

$$.6$$

$$.5$$

$$.4$$

$$.3$$

$$.2$$

$$.15$$

$$.10$$

$$.05$$

$$.02$$

$$.01$$

$$.005$$

$$.002$$

$$.001$$

$$.0005$$

$$.0002$$

$$.0001$$

$$.00005$$

$$.00002$$

$$.00001$$

$$.000005$$

$$.000002$$

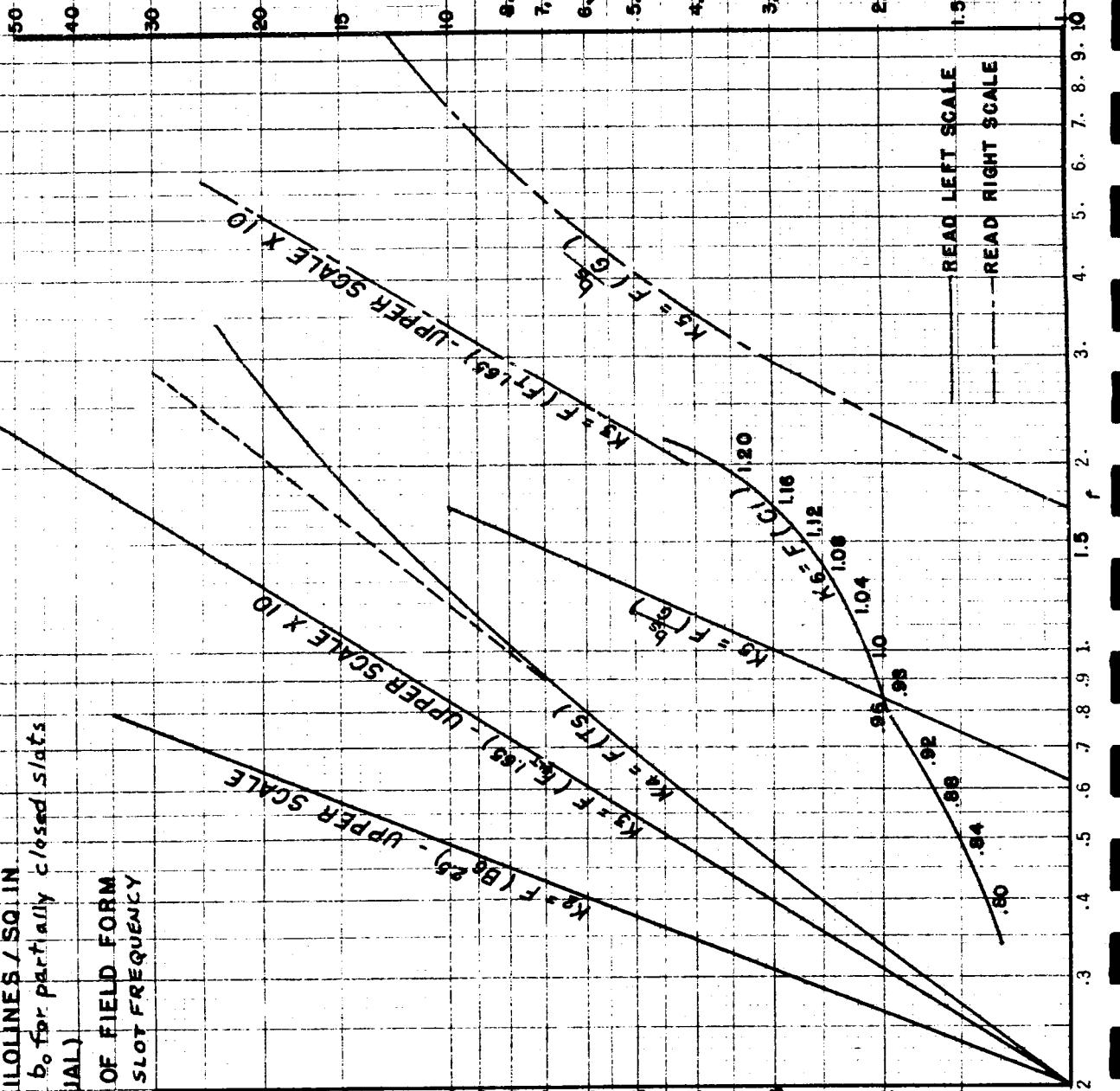
$$.000001$$

$$.0000005$$

$$.0000002$$

$$.0000001$$

$$.00000005$$



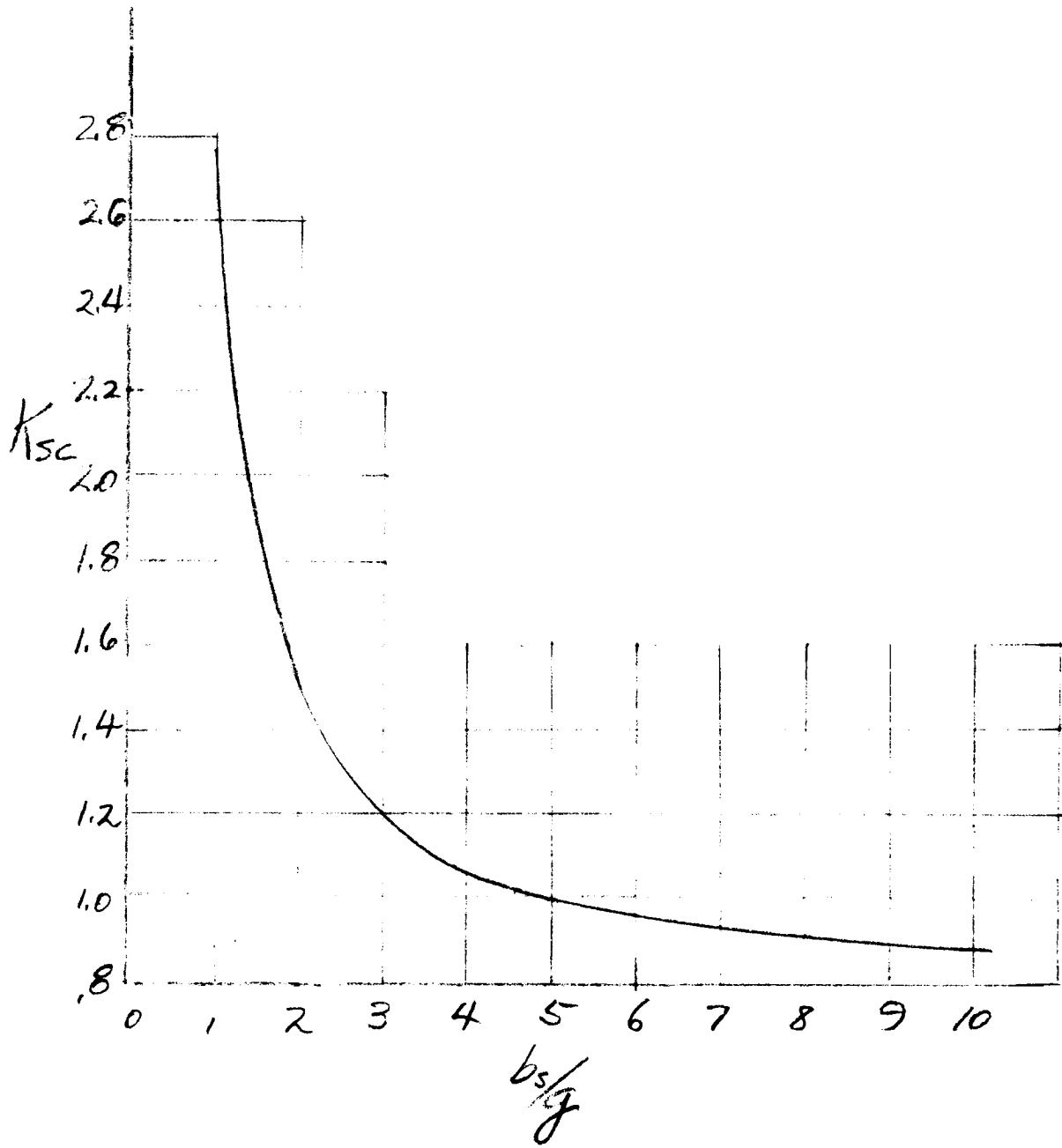
READ LEFT SCALE

READ RIGHT SCALE

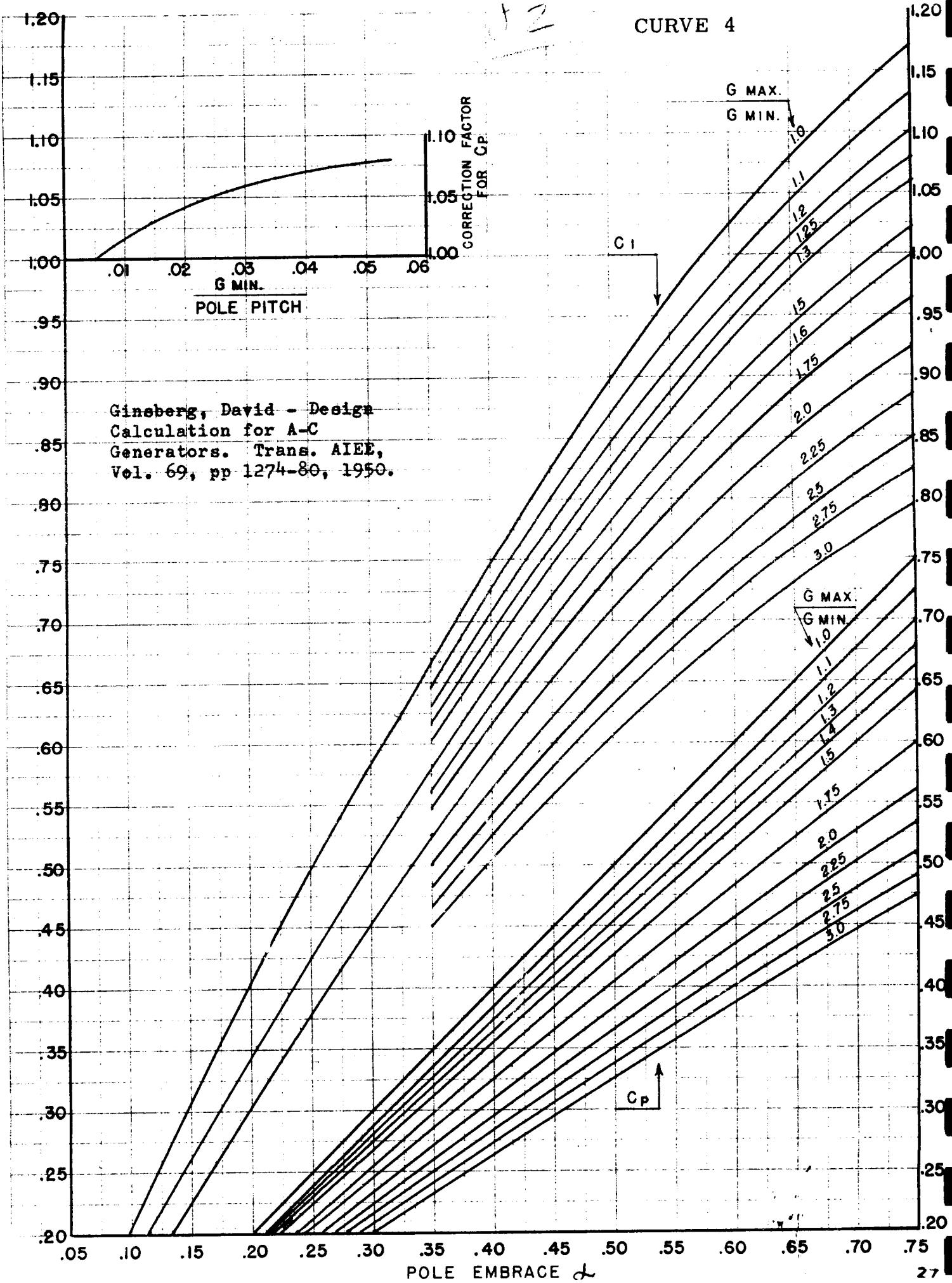
DRAWN BY
J.A.T.

CURVE 3

FROM E.I. POLLARD "LOAD LOSSES IN SAWENT POLE SYNCHRONOUS MACHINES" AIEE TRANS VOL 54, 1935 PP 1332-1340



CURVE 4

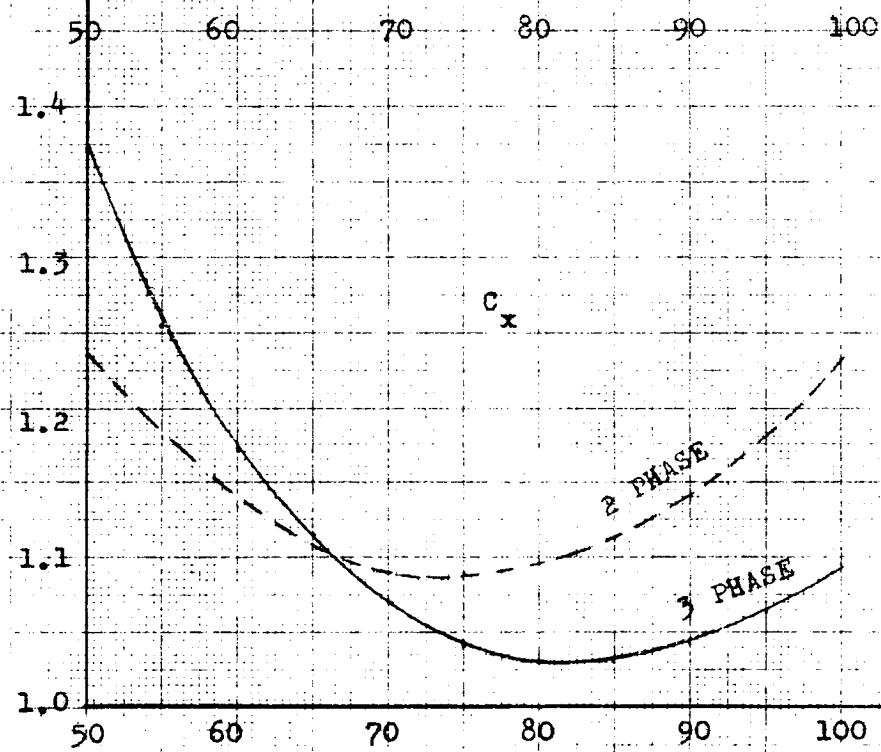


CURVE 5

PERCENT COIL EMBRACE

K.E. - SLOT FACTOR FOR APPROXIMATE REACTANCE FORMULA

K.E. 10 X 10 TO THE CM. 359-14
KUFFEL & ESSER CO., NEW YORK



PERCENT COIL EMBRACE

NO-LOAD DAMPER LOSS

CURVE 7

$$D.L. = \frac{1.246 P n_b l_b P}{10^6 a_b} \left[\frac{T_s B_g K_p K_g}{L_s} \right]^2 \left[\frac{K_f / K_w}{2\lambda_s + \lambda_g} \right]^2 + \left[\frac{K_f / K_w}{2\lambda_s + \lambda_g} \right]^2$$

= LOSS IN KW

$$\lambda_s = \frac{hr}{br} + \lambda_t + \lambda_c$$

a_b = BAR AREA IN SQ IN.

n_b = BARS/POLE

$$\lambda_g = \frac{T_b}{K_g g} = \frac{T_b}{g'}$$

P = NO. POLES

l_b = LENGTH BAR IN.

ARMATURE

K_g = CARTER'S COEFFICIENT (TOTAL)

$K_p = f_n(b_s/g)$, CURVE (a) ($b_s + b_o$ for partially closed slots)

K_f_1 AND $K_f_2 = f_n(f_s/f)$ CURVE (b)

ρ = DAMPER BAR RESISTIVITY
(MICROHMS PER CU. IN.)

K_w_1 AND $K_w_2 = f_n(b_s/T_s)$, CURVE (c₁) AND (c₂)

K_{ϕ_1} AND $K_{\phi_2} = f_n(T_b/T_s)$, CURVE (d₁) AND (d₂)

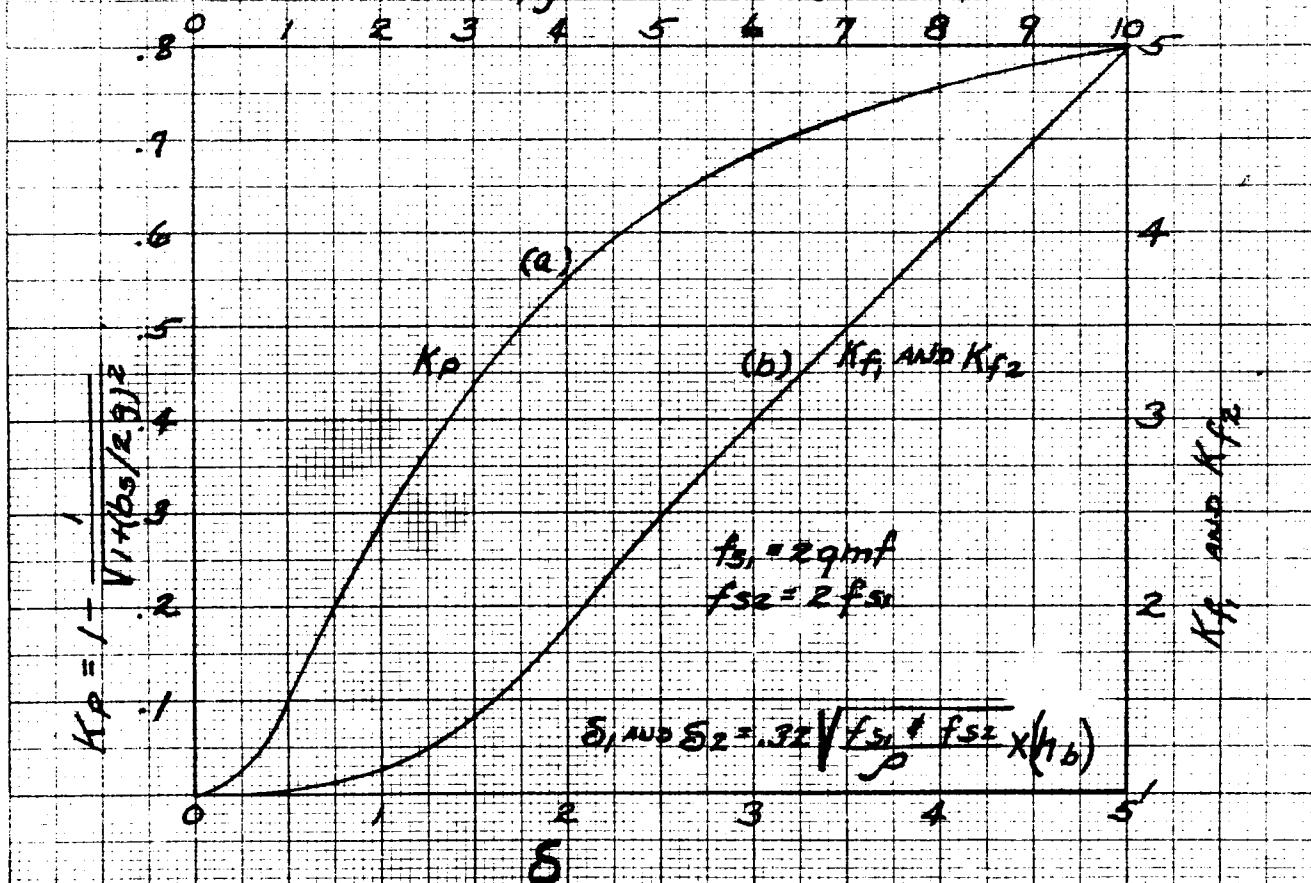
$\lambda_c = f_n(br/g K_g)$ CURVE (e)

B_g IS IN KILOINES PER 50 INCH

$\lambda_c = \frac{75}{K_p}$ (FOR ROUND OR SQ. BARS)

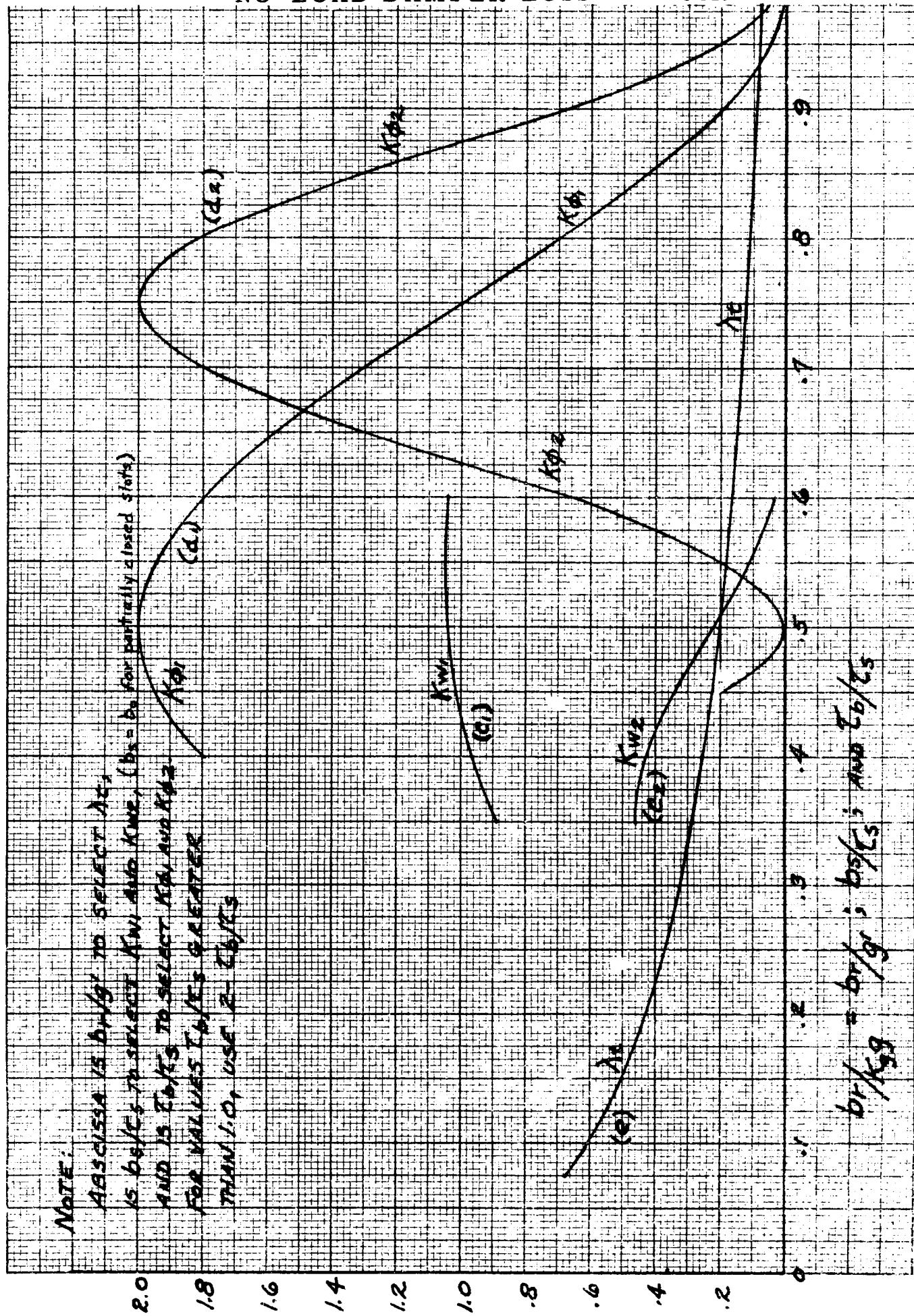
$\lambda_c = \frac{hr}{3bb K_{\phi}}$ (FOR RECT. BARS)

b_s/g (open slots) & b_o/g (partially closed slots)



NO-LOAD DAMPER LOSS

CURVE 8



CURVE 9

PERCENT POLE EMBRACE

50

60

70

80

90

1.0

.8

.6

.4

.2

0

C_m
&
C_{q'}

K+E
10 X 10 TO THE CM. 359-14
KEUFFEL & TESSER CO., NEW YORK U.S.A.

C_m

C_{q'}

CONCENTRIC
AVERAGE POLE SHAPE

SINE WAVE POLE

50

60

70

80

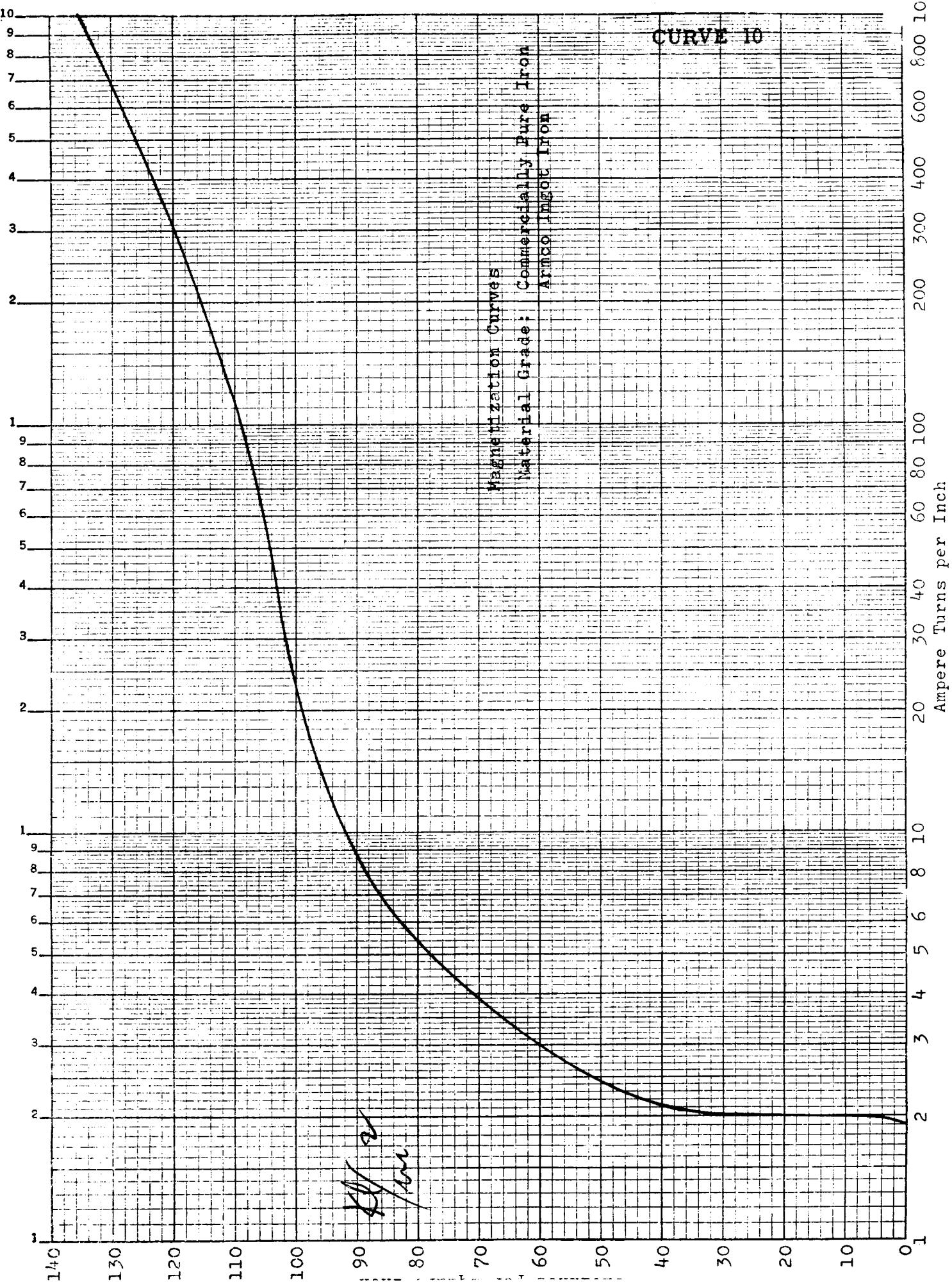
90

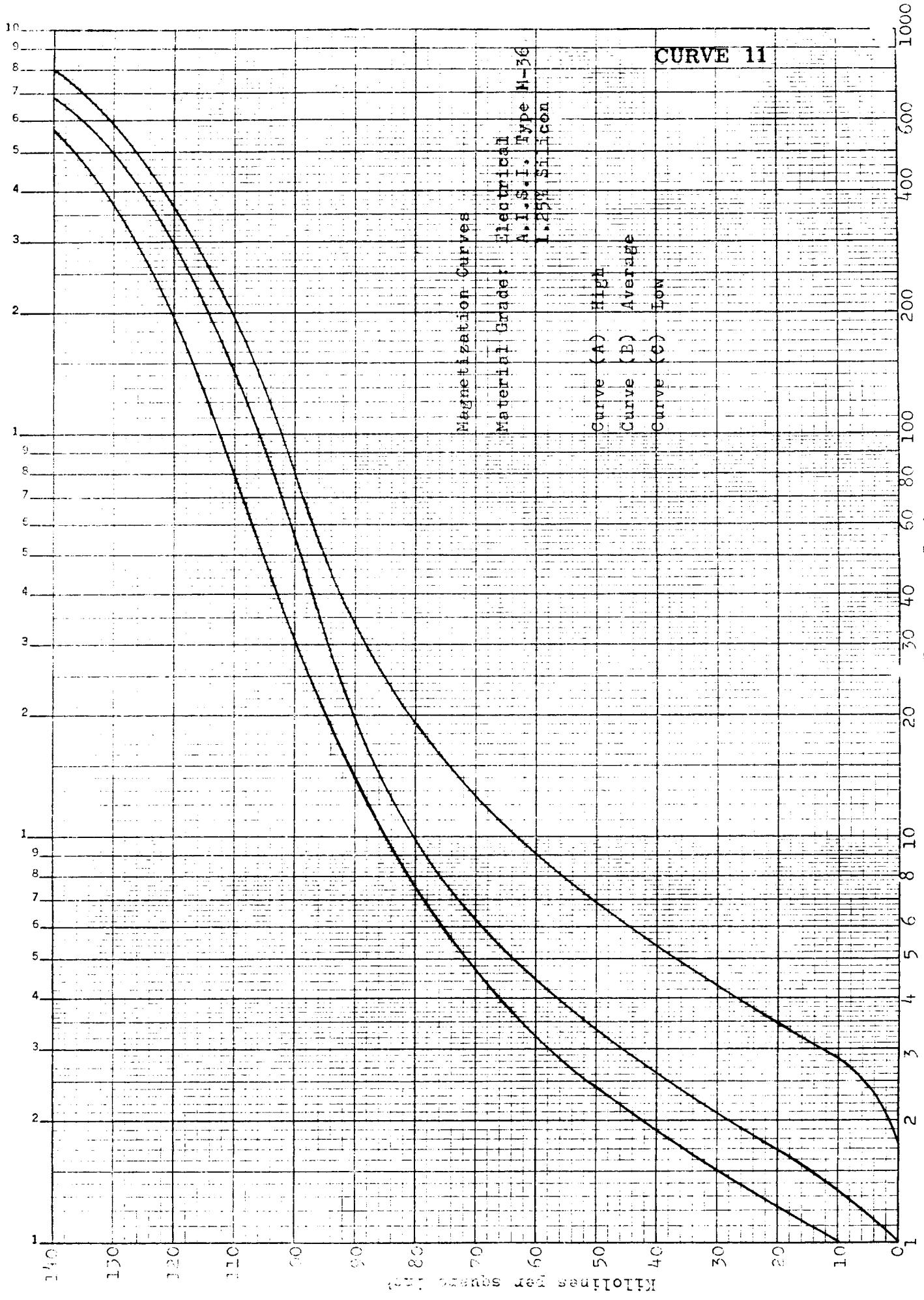
PERCENT POLE EMBRACE

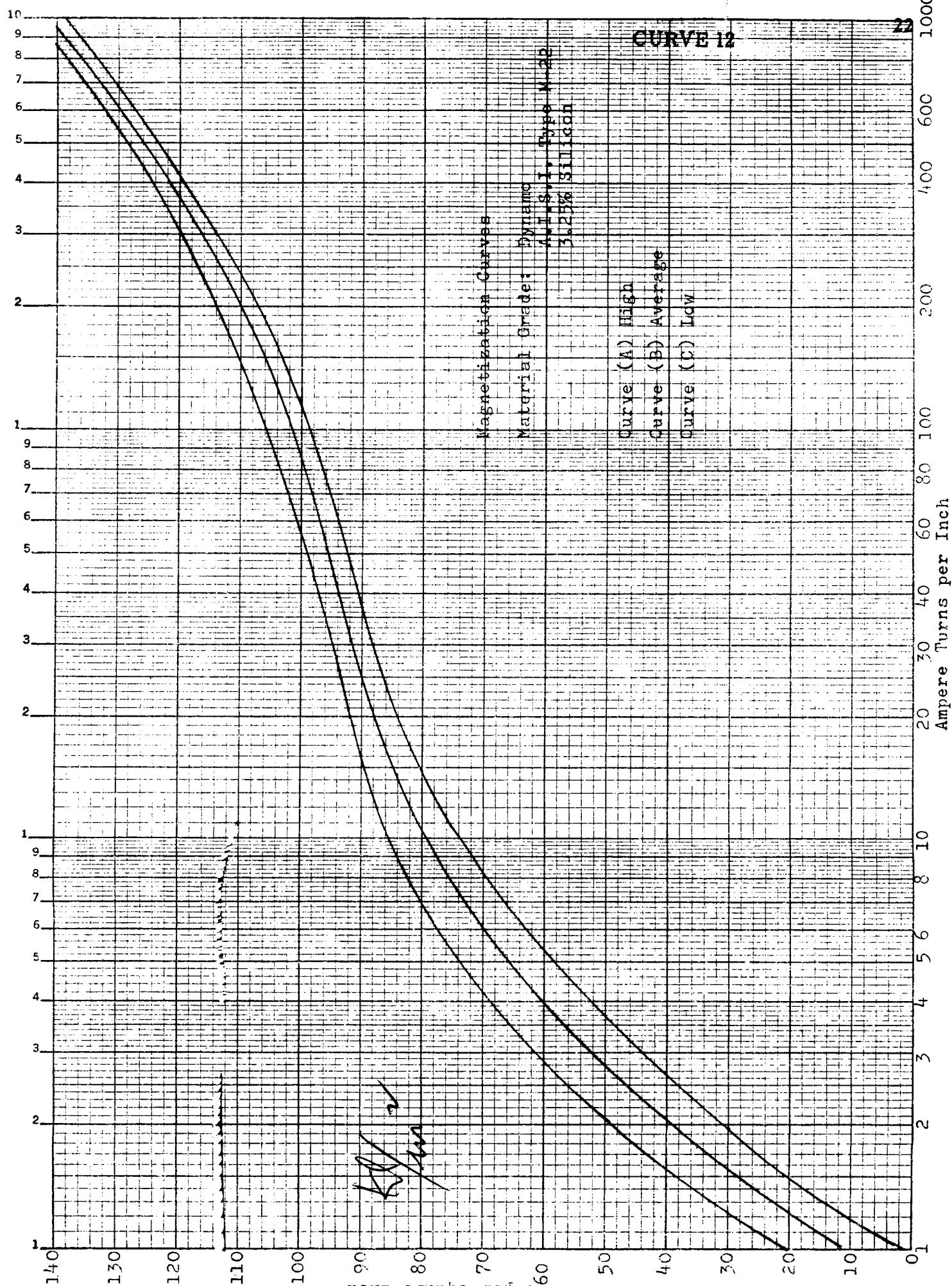
SALIENT POLE MACHINE CONSTANTS

C_m C_{q'}

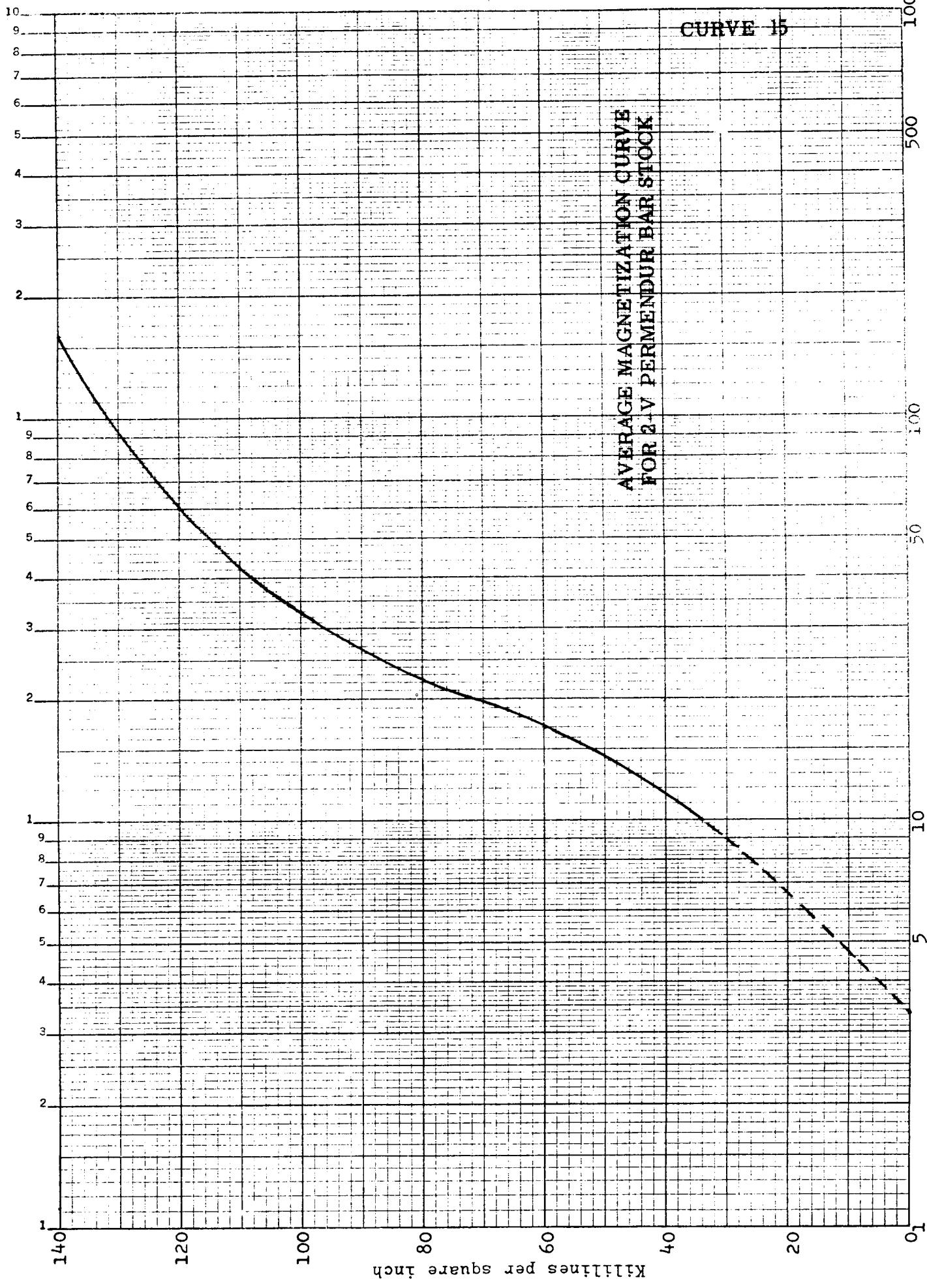
CURVE 10



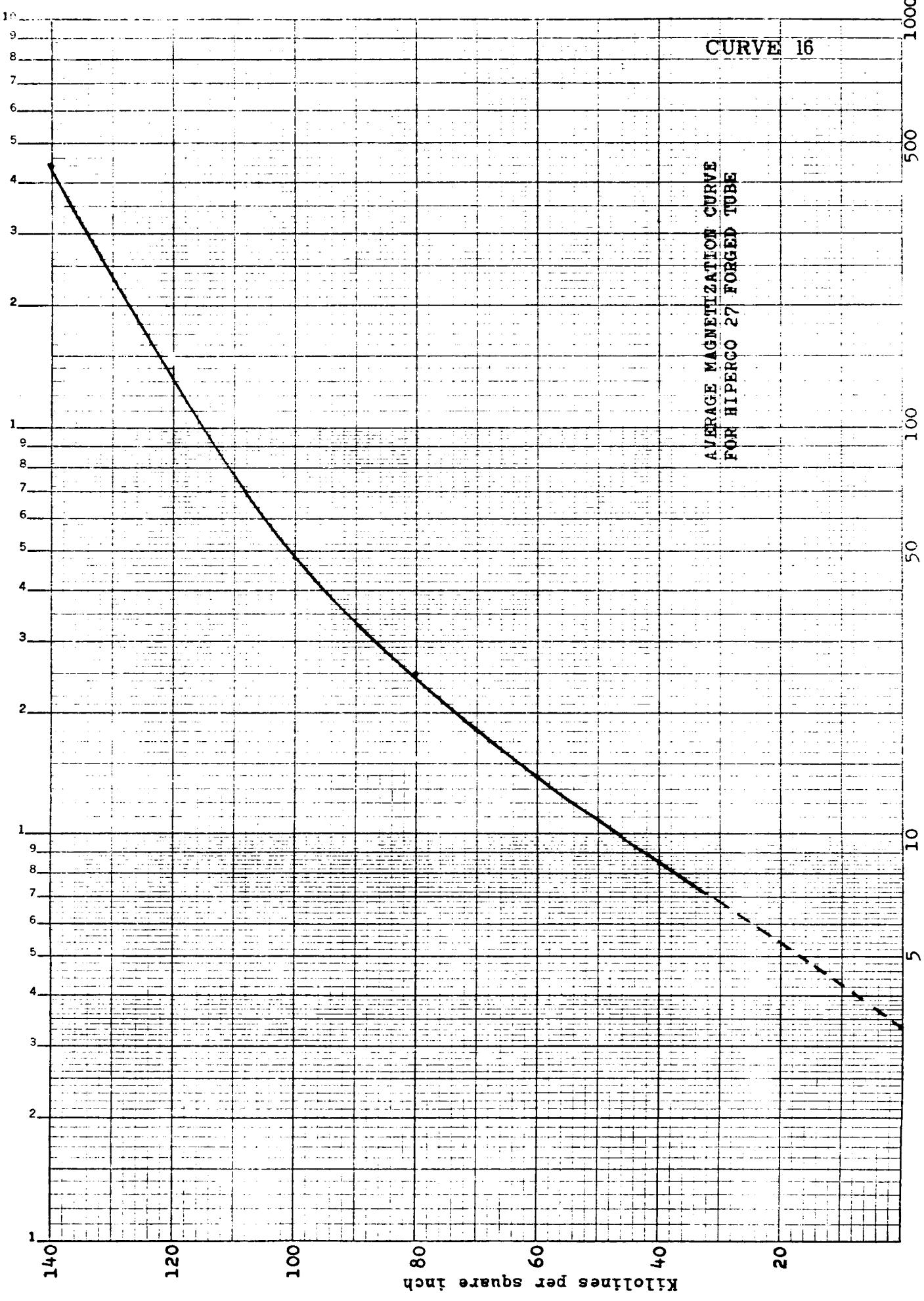




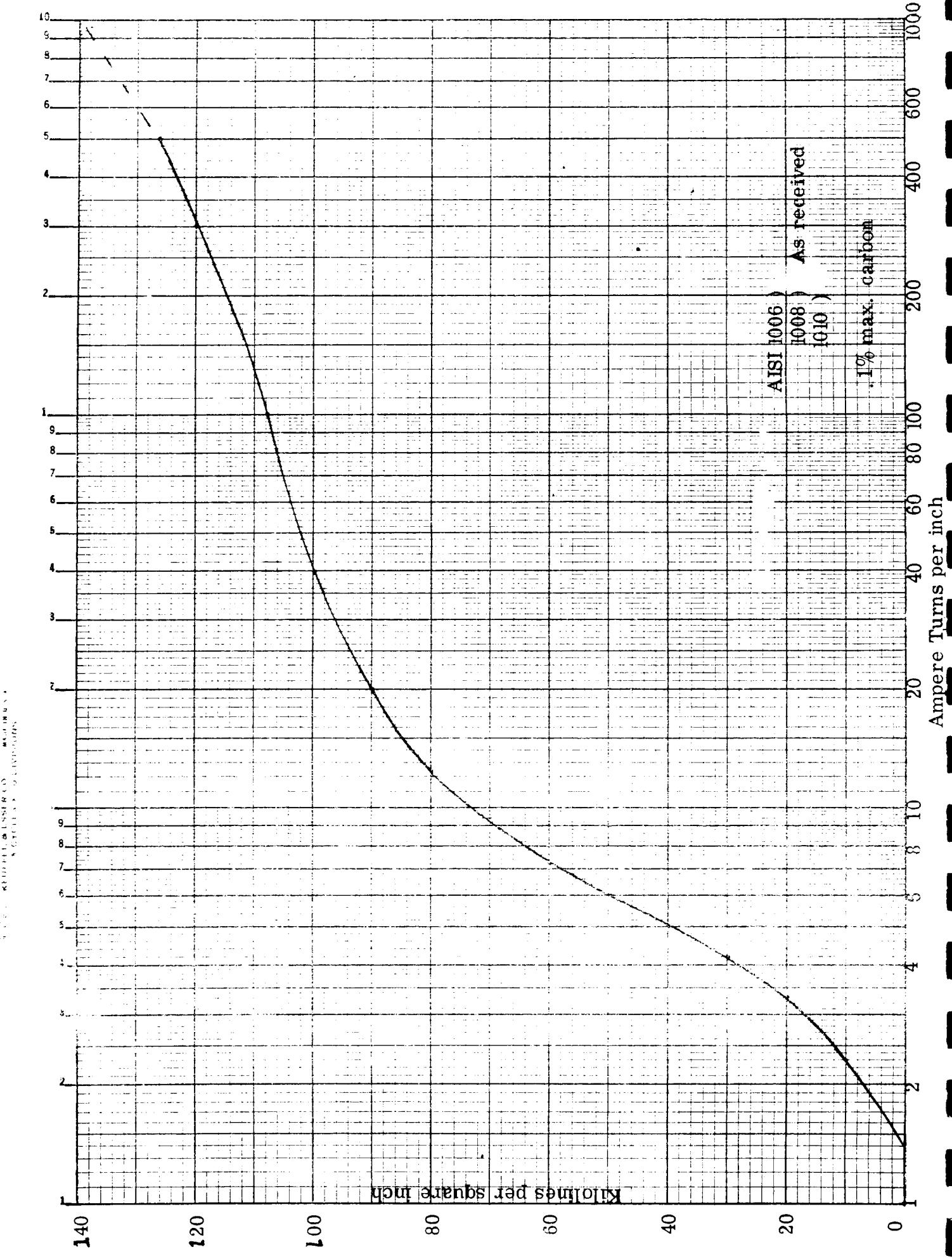
KELLOGG
SEMI-LOGARITHMIC
KELLOGG & ESSER CO.
3 CYCLES X 72 DIVISIONS



K-25 SEMI-LOGARITHMIC
KEUFFEL & ESSER CO. NEW YORK
1 CYCLES X 70 DIVISIONS



CURVE 17



(1)	--	<u>DESIGN NUMBER</u> - To be used for filing purposes
(2)	KVA	<u>GENERATOR KVA</u>
(3)	E	<u>LINE VOLTS</u>
(4)	E_{PH}	<u>PHASE VOLTS</u> - For 3 phase, connected generator $E_{PH} = \frac{(\text{Line Volts})}{\sqrt{3}} = \frac{(3)}{\sqrt{3}}$ For 3 phase, connected generator $E_{PH} = (\text{Line Volts}) = (3)$
(5)	m	<u>PHASES</u> - Number of
(5a)	f	<u>FREQUENCY</u> - In cycles per second
(6)	P	<u>POLES</u> - Number of
(7)	RPM	<u>SPEED</u> - In revolutions per minute
(8)	I_{PH}	<u>PHASE CURRENT</u> - In amperes at rated load
(9)	P.F.	<u>POWER FACTOR</u> - Given in per unit
(9a)	K_c	<u>ADJUSTMENT FACTOR</u> - When P. F. = 0. to .95 set $K_c = 1.$; when P. F. = .95 to 1. set $K_c = 1.05$
(10)	--	<u>LOAD POINTS</u> - The computer program is set up to have the 0.%, 100%, 150%, 200% load points as standard outputs. There is an additional space available on the output sheet for one optional load point. This optional

load point will be the designer's choice and can be selected anywhere in the range of 0 to 200% load. When an optional load calculation is required, insert the per unit load value on the input sheet. The optional load point will be calculated in addition to the standard points listed above. For example, insert .33 on the input sheet when the optional load calculation for 33% load is required in addition to the standard points.

If only the standard points are required, insert 0.0 on the input sheet and the optional load column will be blank.

- | | | |
|-------|-------|--|
| (11) | d | <u>STATOR PUNCHING I.D.</u> - The inside diameter of the stator punching in inches. |
| (11a) | d_r | <u>ROTOR O.D.</u> - The outside diameter of the rotor in inches. |
| (12) | D | <u>PUNCHING O.D.</u> - The outside diameter of the stator punching in inches. |
| (13) | | <u>GROSS STATOR CORE LENGTH</u> - In inches. |
| (14) | n_v | <u>RADIAL DUCTS</u> - Number of. |
| (15) | b_v | <u>RADIAL DUCT WIDTH</u> - In inches. |
| (16) | K_i | <u>STACKING FACTOR</u> - This factor allows for the coating (core plating) on the punchings, the burrs due to slotting, and the deviations in flatness. Approximate values of K_i are given in Table IV. |

THICKNESS OF LAMINATIONS (INCHES)	GAGE	K _i
.014	29	0.92
.018	26	0.93
.025	24	0.95
.028	23	0.97
.063	--	0.98
.125	--	0.99

TABLE IV

(17)

 ℓ_s

SOLID CORE LENGTH - The solid length is the gross length times the stacking factor. If ventilating ducts are used, their length must be subtracted from the gross length also.

$$\ell_s = (K_i) \left[(\ell) - (n_v) (b_v) \right] = (16) \left[(13) - (14) (15) \right]$$

(18)

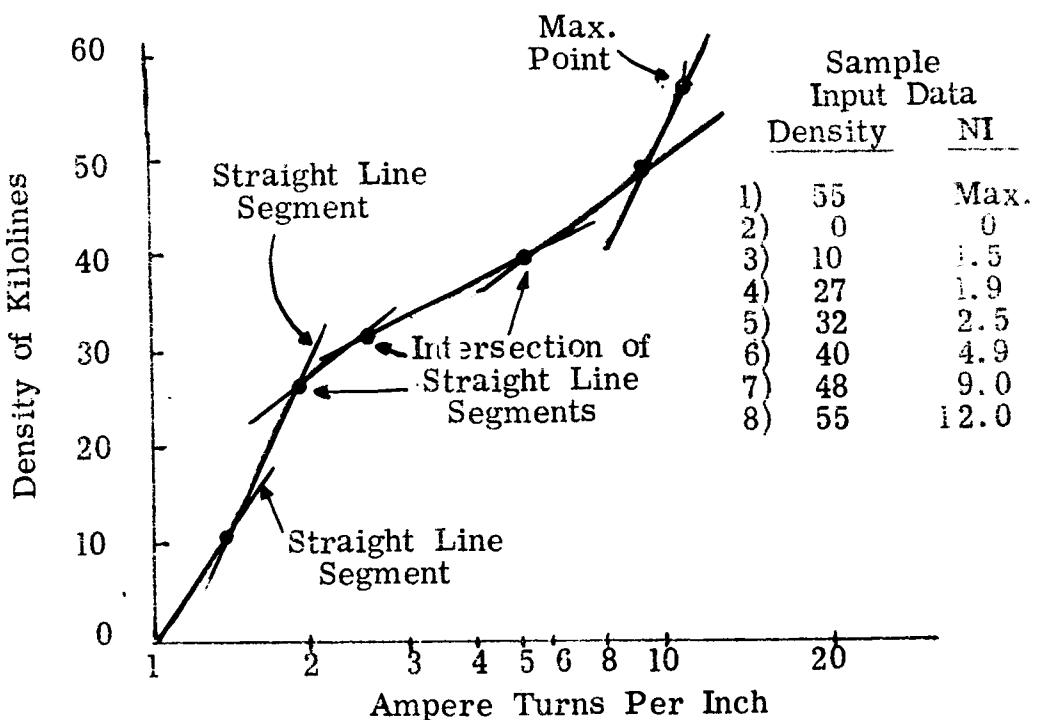
MATERIAL - This input is used in selecting the proper magnetization curves for stator;

yoke; pole and shaft; when different materials are used. Separate spaces are provided on the input sheet for each section mentioned above. Where curves are available on card decks, used the proper identifying code. Where card decks are not available submit data in the following manner:

The magnetization curve must be available on semi-log paper. Typical curves are shown in this manual on Curves 15 and 16. Draw straight line segments through the curve starting with zero density. Record the coordinates of the points where the

straight line segments intersect. Submit these coordinates as input data for the magnetization curve. The maximum density point must be submitted first.

Refer to Figure below for complete sample



- (19) k WATTS/LB - Core loss per lb of stator lamination material.
Must be given at the density specified in (20).
- (20) B DENSITY - This value must correspond to the density used
in Item (19) to pick the watts/lb. The density that
is usually used is 77.4 kilolines/in².

(21)

1

TYPE OF STATOR SLOT - Refer to Figure 1

2

for type of slot.

3

For (a) slot use 1. as an input

4

For (b) slot use 2. as an input

5

For (c) slot use 3. as an input

For (d) slot use 4. as an input

Type 5. is not a slot but instead a particular situation for an open slot where the winding has only one conductor per slot.

(22)

b₀b₁b₂b₃b_sh₀h₁h₂h₃h_sh_th_wALL SLOT DIMENSIONS - Given in inches per Figure 1.

Where the dimension does not apply

to the slot being used, insert 0. on input sheet.

NOTE: FOR TYPE (C) SLOT

$$b_s = \frac{(b_1) + (b_3)}{2} = \frac{(z_2) + (z_2)}{2}$$

(23)

Q

STATOR SLOTS - Number of.

(24)

h_cDEPTH BELOW SLOTS - The depth of the stator core below
the slots.

Due to mechanical strength reasons, h_c should never be less than 70% of h_s .

$$h_c = \frac{(D) - [(d) + 2(h_s)]}{2} = \frac{(12) - [(11) + 2(22)]}{2}$$

(25) q SLOTS PER POLE PER PHASE

$$q = \frac{(Q)}{(P)(m)} = \frac{(23)}{(6)(5)}$$

(26) T_s STATOR SLOT PITCH

$$T_s = \frac{\pi(d)}{Q} = \frac{\pi(11)}{(23)}$$

(27) $T_{s1/3}$ STATOR SLOT PITCH - 1/3 distance up from narrowest section. For slot (a), (b), (c), and (e)

$$T_{s1/3} = \frac{\pi[(d) + .66(h_s)]}{(Q)} = \frac{\pi[(11) + .66(22)]}{(23)}$$

For slot (d)

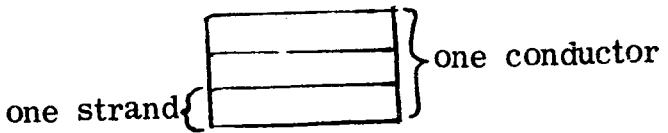
$$\frac{\pi[(d) + 2(h_0) + 1.32(b_s)]}{(Q)} = \\ \frac{\pi[(11) + 2(22) + 1.32(22)]}{(23)}$$

(28) -- TYPE OF WINDING - Record whether the connection is "wye" or "delta". For "wye" conn use 1. for input. For "delta" use 0. for input.

(29) -- TYPE OF COIL - Record whether random wound or formed coils are used. For random wound coils use 0. for input. For formed coils use 1. for input.

- (30) ns CONDUCTORS PER SLOT - The actual number of conductors per slot. For random wound coils use a space factor of 75% to 80%. Where space factor is the percent of the total slot area that is available for insulated conductors after all other insulation areas have been subtracted out.
- (31) Y THROW - Number of slots spanned. For example, with a coil side in slot 1 and the other coil side in slot 10, the throw is 9.
- (31a) PER UNIT OF POLE PITCH SPANNED - Ratio of the number of slots spanned to the number of slots in a pole pitch. This value must be between 1.0 and 0.5 to satisfy the limits of this program.
- $$= \frac{(Y)}{(m)(q)} \quad \frac{(31)}{(5)(25)}$$
- (32) C PARALLEL PATHS, No. of - Number of parallel circuits per phase.
- (33) -- STRAND DIA. OR WIDTH - In inches. For round wire, use strand diameter. For rectangular wire, use strand width. This must be the largest of the two dimensions given for a rectangular wire.
- (34) NST NUMBER OF STRANDS PER CONDUCTOR IN DEPTH - Applies to rectangular wire. In order to have a more flexible conductor and reduce eddy current loss, a stranded conductor is often used. For

example, when the space available for one conductor is .250 width x .250 depth, the actual conductor can be made up of 2 or 3 strands in depth as shown



For a more detailed explanation refer to section titled "Effective Resistance and Eddy Factor" in the Derivations in Appendix.

(34a)	N' ST	<u>NUMBER OF STRANDS PER CONDUCTOR</u> - This number applies to the strands in depth and/or width and is used in calculating the conductor area. Item (34) is different in that it deals with strands in depth only and is used in calculating eddy factors.
(35)	d_b	<u>DIAMETER OF BENDER PIN</u> - in inches - This pin is used in forming coils. Use .25 inch for stator O.D. < 8 inches use .50 inches for stator O.D. > 8 inches.
(36)	ℓ_{e2}	<u>COIL EXTENSION BEYOND CORE</u> in Inches - Straight portion of coil that extends beyond stator core.
(37)	h_{ST}	<u>HEIGHT OF UNINSULATED STRAND</u> in Inches - This value is the vertical height of the strand and is used in eddy factor calculations. Set this value = 0 for round wire.
(38)	h' ST	<u>DISTANCE BETWEEN CENTERLINES OF STRANDS IN DEPTH</u> in inches.

- (39) -- STATOR COIL STRAND THICKNESS in inches - For rectangular conductors only. For round wire insert 0. on input sheet. This must be the narrowest dimension of the two dimensions given for a rectangular wire.
- (40) τ_{SK} SKEW - Stator slot skew in inches at stator I.D.
- (41) τ_P POLE PITCH in inches.

$$\tau_P = \frac{\pi(d)}{(P)} = \frac{\pi(11)}{(6)}$$
- (42) K_{SK} SKEW FACTOR - The skew factor is the ratio of the voltage induced in the coils to the voltage that would be induced if there were no skew.
When $\tau_{SK} = 0$, $K_{SK} = 1$

$$K_{SK} = \frac{\sin \left[\frac{\pi(\tau_{SK})}{2(\tau_P)} \right]}{\frac{\pi(\tau_{SK})}{2(\tau_P)}} = \frac{\sin \left[\frac{\pi(40)}{2(41)} \right]}{\frac{\pi(40)}{2(41)}}$$
- (42a) PHASE BELT ANGLE - Input
For phase belt angle = 60° insert 60 on input sheet.
For phase belt angle = 120° insert 120 on input sheet.
- (43) K_d DISTRIBUTION FACTOR - The distribution factor is the ratio of the voltage induced in the coils to the voltage that would be induced if the windings

were concentrated in a single slot. See Table 2 for compilation of distribution factors for the various harmonics.

For 60° phase belt angle and $q = \text{integer}$ when
 $(42a) = 60$ and $(25) = \text{integer}$.

$$K_d = \frac{\sin 30^\circ}{(q) \sin [30/(q)]} = \frac{\sin 30^\circ}{(25) \sin [30/(25)]}$$

For 60° phase belt angle and $(q) \neq \text{integer} = N/B$ reduced to lowest terms.

When $(43a) = 1$ and $(25) \neq \text{integer} = N/B$ reduced to lowest terms

$$K_d = \frac{\sin 30^\circ}{(N) \sin [30/(N)]} = \frac{\sin 30^\circ}{(43) \sin [30/(43)]}$$

For 120° phase belt angle and $(q) = \text{integer}$

When $(43a) = 120$ and $(25) = \text{integer}$

$$K_d = \frac{\sin 60^\circ}{2(q) \sin [30/(q)]} = \frac{\sin 60^\circ}{2(25) \sin [30/(25)]}$$

For 120° phase belt angle and $q = \text{integer}$

When $(43a) = 120$ and $(25) \neq \text{integer} = N/B$ reduced to lowest terms

$$K_d = \frac{\sin 60^\circ}{2(N) \sin [30/(N)]} = \frac{\sin 60^\circ}{2(43) \sin [30/(43)]}$$

(44)

 K_p

PITCH FACTOR - The ratio of the voltage induced in the coil to the voltage that would be induced in a full pitched coil. See Table 1 for compilation of the pitch factors for the various harmonics.

$$K_p = \sin \left[\frac{(Y)}{(m)(q)} \times 90^\circ \right] = \sin \left[\frac{(31)}{(5)(25)} \times 90^\circ \right]$$

(45)

 n_e

TOTAL EFFECTIVE CONDUCTORS - The actual number of effective series conductors in the stator winding taking into account the pitch and skew factors but not allowing for the distribution factor.

$$n_e = \frac{(Q)(n_s)(K_p)(K_{SK})}{(C)} = \frac{(23)(30)(44)(42)}{(32)}$$

(46)

 a_c

CONDUCTOR AREA OF STATOR WINDING in (inches)² -

The actual area of the conductor taking into account the corner radius on square and rectangular wire. See the following table for typical values of corner radii

$$\text{If } (39) = 0 \text{ then } a_c = .25\pi(\text{Dia})^2 = .25\pi(33)^2$$

$$\text{If } (39) \neq 0 \text{ then } a_c = (N' ST) \left[(\text{strand width})(\text{strand depth}) - (.858 r_c^2) \right] = (34a) \left[(33)(39) - (.858 r_c^2) \right]$$

where $.858 r_c^2$ is obtained from Table V below.

(39)	(33) .188	.189 (33) .75	(33) .751
.050	.000124	.000124	.000124
.072	.000210	.000124	.000124
.125	.000210	.00084	.000124
.165	.000840	.00084	.003350
.225	.001890	.00189	.003350
.438	--	.00335	.007540
.688	--	.00754	.01340
--	--	.03020	.03020

TABLE V

(47) s_s CURRENT DENSITY - Amperes per square inch of stator conductor

$$s_s = \frac{(I_{PH})}{(C)(a_c)} = \frac{(8)}{(32)(46)}$$

(48) L_E END EXTENSION LENGTH in inches - Can be an input or output.

For L_E to be output, insert 0. on input sheet.

For L_E to be input, calculate per following:

When (29) = 0. then:

$$L_E = .5 + \frac{K_T \pi(Y)[(d)+(h_s)]}{Q} = .5 + \frac{\begin{cases} 1.3 & \text{If } (6) = 2 \\ 1.5 & \text{If } (6) = 4 \\ 1.7 & \text{If } (6) = 4 \end{cases}}{(23)} \pi(31)[(11)+(22)]$$

When (29) = 1. then:

$$\begin{aligned} L_E &= 2 \ell_{e2} + \pi \left[\frac{h_1}{2} + \text{dia} \right] + y \left[\frac{T_s^2}{\sqrt{T_s^2 - b_s^2}} \right] \\ &= 2 (36) + \pi \left[\frac{(22)}{2} + (35) \right] + (31) \left[\frac{(26)^2}{\sqrt{(26)^2 - (22)^2}} \right] \end{aligned}$$

(49) ℓ_t 1/2 MEAN TURN - The average length of one conductor in inches.

$$\ell_t = (\ell) + (L_E) = (13) + (44)$$

(50) $x_s {}^\circ C$ STATOR TEMP {}^\circ C - Input temp at which F.L. losses will be calculated. No load losses and cold resistance will be calculated at 20 ${}^\circ C$.

(51)

 ρ_s

RESISTIVITY OF STATOR WINDING - In micro ohm-inches @ 20°C. If tables are available using units other than that given above, use Table VI for conversion to ohm-inches.

ρ	ohm-cm	ohm-in	ohm-cir mil/ft
1 ohm-cm =	1.000	0.3937	6.015×10^6
1 ohm-in =	2.540	1.000	1.528×10^7
1 ohm-cir mil/ft =	1.662×10^{-7}	6.545×10^{-8}	1.000

TABLE VI
Conversion Factors for Electrical Resistivity

(52)

 ρ_s
(hot)

RESISTIVITY OF STATOR WINDING - Hot at X_s °C in micro ohm-inches

$$\rho_{s(\text{hot})} = (\rho_s) \left[\frac{(X_s \text{ } ^\circ\text{C}) + 234.5}{254.5} \right] = (51) \left[\frac{(50) + 234.5}{254.5} \right]$$

(53)

R_{SPH}
(cold)

STATOR RESISTANCE/PHASE - Cold @ 20°C in ohms

$$R_{\text{SPH}(\text{cold})} = \frac{(\rho_s)(n_s)(Q)(l_t)}{(m)(a_c)(C)^2} \times 10^{-6} = \frac{(51)(30)(23)(49)}{(5)(46)(32)^2} \times 10^{-6}$$

(54)

R_{SPH}
(hot)

STATOR RESISTANCE/PHASE - Calculated @ X°C in ohms

$$R_{\text{SPH}(\text{hot})} = \frac{(\rho_s \text{ hot})(n_s)(Q)(l_t)}{(m)(a_c)(C)^2} \times 10^{-6} \frac{(52)(30)(23)(49)}{(5)(46)(32)^2} \times 10^{-6}$$

(55)

EF
(top)

EDDY FACTOR TOP - The eddy factor of the top coil. Calculate this value at the expected operating temperature of the machine. For round wire

$$EF_{\text{top}} = 1$$

$$\begin{aligned}
 EF_{top} &= 1 + \left\{ .584 + \left[\frac{N_{st}^2 - 1}{16} \right] \left[\frac{h'_{st} l}{h_{st} l_t} \right]^2 \right\} 3.35 \times 10^{-3} \\
 &\quad \left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_{shot})} \right]^2 \\
 &= 1 + \left\{ .584 + \left[\frac{(34)^2 - 1}{16} \right] \left[\frac{(38)(13)}{(37)(49)} \right]^2 \right\} 3.35 \times 10^{-3} \\
 &\quad \left[\frac{(37)(30)(5a)(46)}{(22)(52)} \right]^2
 \end{aligned}$$

(56)

EF
(bot)

EDDY FACTOR BOTTOM - The eddy factor of the bottom coil at the expected operating temperature of the machine. For round wire $EF_{(bot)} = 1$

$$\begin{aligned}
 EF_{(bot)} &= (EF_{(top)}) - 1.677 \left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_{shot})} \right]^2 \times 10^{-3} \\
 &= (55) - 1.677 \left[\frac{(37)(30)(5a)(46)}{(22)(52)} \right] 10^{-3}
 \end{aligned}$$

(57)

btm

STATOR TOOTH WIDTH 1/2 way down tooth in inches -
For slots type (a), (b), (d) and (e), Figure I

$$b_{tm} = \frac{\pi \overline{(d)} + (h_s)}{(Q)} - (b_s) = \frac{\pi \overline{(11)} + (22)}{(23)} - (22)$$

For slot type (c), Figure I

$$b_{tm} = \frac{\pi \overline{(d)} + 2(h_s)}{(Q)} - (b_3) = \frac{\pi \overline{(11)} + 2(22)}{(23)} - (22)$$

(57a)	$b_t \frac{1}{3}$	<u>STATOR TOOTH WIDTH</u> $\frac{1}{3}$ distance up from narrowest section. For slots type (a), (b) and (e) $b_t \frac{1}{3} = (\tau_s \frac{1}{3}) - (b_s) = (27) - (22)$ For slot type (c) $b_t \frac{1}{3} = b_{tm} = (57)$ For slot type (d) $b_t \frac{1}{3} = (\tau_{1/3}) - \frac{2\sqrt{2}}{3} (b_s) = (27) - .94(22)$
(58)	b_t	<u>TOOTH WIDTH AT STATOR I.D.</u> in inches - For partially closed slot $b_t = \frac{\pi r(d)}{(Q)} - b_o = \frac{\pi(11)}{(23)} - (22)$ For open slot $b_t = \frac{\pi r(d)}{(Q)} - b_s = \frac{\pi(11)}{(23)} - (22)$
(59)	g	<u>MAIN AIR GAP</u> in inches
(60)	C_X	<u>REDUCTION FACTOR</u> - Used in calculating conductor permeance and is dependent on the pitch and distribution factor. This factor can be obtained from Graph 1 with an assumed K_d of .955 or calculated as shown. $C_X = \frac{(K_X)}{(K_p)^2 (K_d)^2} = \frac{(61)}{(44)^2 (43)^2}$

(61) K_X

FACTOR TO ACCOUNT FOR DIFFERENCE in phase current
in coil sides in same slot.

For 60° phase belt winding, i.e. when (42a) = 60

$$K_X = 1/4 \left[\frac{3(y)}{(m)(q)} + 1 \right] \text{ where } 2/3 \leq (y)/(m)(q) \leq 1.0$$

$$K_X = 1/4 \left[\frac{3(3l)}{(5)(25)} + 1 \right] \text{ where } 2/3 \leq (3la) \leq 1.0$$

or

$$K_X = 1/4 \left[\frac{6(y)}{(m)(q)} - 1 \right] \text{ where } 1/2 \leq (3la) \leq 2/3$$

$$K_X = 1/4 \left[\frac{6(3l)}{(5)(25)} - 1 \right] \text{ where } 1/2 \leq (3la) \leq 2/3$$

For 120° phase belt winding, i.e. when (42a) = 120

$$K_X = .75 \text{ when } 2/3 \leq (y)/(m)(q)$$

$$K_X = .75 \text{ when } 2/3 \leq (3la)$$

or

$$K_X = .05 \left[\frac{24(y)}{(m)(q)} - 1 \right] \text{ where } 1/2 \leq \frac{(y)}{(m)(q)} \leq 2/3$$

$$K_X = .05 \left[\frac{24(3l)}{(3)(25)} - 1 \right] \text{ where } 1/2 \leq (3la) \leq 2/3$$

(62) λ_i

CONDUCTOR PERMEANCE - The specific permeance for
the portion of the stator current that is embedded
in the iron. This permeance depends upon the
configuration of the slot.

(a) For open slots

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)} \right]$$

(b) For partially closed slots with constant slot width

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_o)}{(b_o)} + \frac{2(h_t)}{(b_o) + (b_s)} + \frac{(h_w)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{2(22)}{(22) + (22)} + \frac{(22)}{(22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)} \right]$$

(c) For partially closed slots (tapered sides)

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_o)}{(b_o)} + \frac{2(h_t)}{(b_o) + (b_1)} + \frac{2(h_w)}{(b_1) + (b_2)} + \frac{(h_1)}{3(b_2)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{2(22)}{(22) + (22)} + \frac{2(22)}{(22) + (22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)} \right]$$

(d) For round slots

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[.62 + \frac{(h_o)}{(b_o)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[.62 + \frac{(22)}{(22)} \right]$$

(e) For open slots with a winding of one conductor per slot

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + .6 + \frac{(g)}{2(\tau_s)} + \frac{(\tau_s)}{4(g)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{(22)}{3(22)} + .6 + \frac{(59)}{2(26)} + \frac{(26)}{4(59)} \right]$$

(63) K_E LEAKAGE REACTIVE FACTOR for end turn

$$K_E = \frac{\text{Calculated value } (L_E)}{\text{Value } (L_E) \text{ from Graph 1}} \quad (\text{For machines where } (11) > 8'')$$

where $L_E = (48)$ and abscisa of Graph 1 = $(Y)(T_s') = (31)(26)$

$$K_E = \sqrt{\frac{\text{Calculated value of } (L_E)}{\text{Value } (L_E) \text{ from Graph 1}}} \quad (\text{For machines where } (11) < 8'')$$

(64) λ_E END WINDING PERMEANCE - The specific permeance for the end extension portion of the stator winding

$$\lambda_E = \frac{6.28(K_E)}{(\ell)(K_d)^2} \left[\frac{\phi_E L_E}{2n} \right] = \frac{6.28(63)}{(13)(43)^2} \left[\frac{Q_E L_E}{2n} \right]$$

The term $\left[\frac{\phi_E L_E}{2n} \right]$ is obtained from Graph 1.

The symbols used in this (term) do not apply to those of this design manual. Reference information for the symbol origin is included on Graph 1.

(65) --

WEIGHT OF COPPER - The weight of stator copper in lbs.

$$\# \text{'s copper} = .321(n_S)(Q)(a_C)(\ell_t) = .321(30)(23)(46)(49)$$

NOTE: This answer is given in lbs. based on the density of copper. If any other material is used, the answer on output sheet can be converted by the designer by multiplying by the ratio of densities.

(66) -- WEIGHT OF STATOR IRON - in lbs.

$$\# \text{ s iron} = .283 \left\{ (b_{tm})(Q)(\ell_s)(h_s) + \pi [D] - [h_c] (h_c)(\ell_s) \right\}$$

$$.283 \left\{ (57)(23)(17)(22) + \pi [(12) - (24)] (24)(17) \right\}$$

(67) K_s CARTER COEFFICIENT

$$K_s = \frac{(\tau_s) [5(g) + (b_s)]}{(\tau_s) [5(g) + (b_s)] - (b_s)^2} \quad (\text{For open slots})$$

$$K_s = \frac{(26) [5(59) + (22)]}{(26) [5(59) + (22)] - (22)^2}$$

$$K_s = \frac{\tau_s [4.44(g) + .75(b_o)]}{\tau_s [4.44(g) + .75(b_o)] - (b_o)^2} \quad (\text{For partially closed slots})$$

$$K_s = \frac{(26) [4.44(59) + .75(22)]}{(26) [4.44(59) + .75(22)] - (22)^2}$$

(68) -- MAIN AIR GAP AREA - The area of the gap surface at the stator bore.

$$\text{Gap Area} = \pi(d)(l) = \pi(11)(13)$$

(69) g_e EFFECTIVE AIR GAP

$$g_e = (K_s)(g) = (67)(59)$$

(70) λ_a AIR GAP PERMEANCE - The specific permeance of the air gap

$$\lambda_a = \frac{6.38(d)}{(P)(g_e)} = \frac{6.38(11)}{(6)(69)}$$

(71) C_1 THE RATIO OF MAXIMUM FUNDAMENTAL of the field form to the actual maximum of the field form - This term can be an input or output. For C_1 to be output insert 0. on input sheet. For C_1 to be input, determine C_1 as follows:

For pole heads with only one radius, C_1 is obtained from Curve #4. The abscissa is "pole embrace" (α) = (77). The graphical flux plotting method of determining C_1 is explained in the section titled "Derivations" in the Appendix.

(72) C_W WINDING CONSTANT - The ratio of the RMS line voltage for a full pitched winding to that which would be introduced in all the conductors in series if the density were uniform and equal to the maximum value. This value can be an input or output. For C_W to be an output, insert 0. on input sheet. For C_W to be an input, calculate as follows:

$$C_W = \frac{(E)(C_1)(K_d)}{\sqrt{2} (E_{PH})(m)} = \frac{(3)(71)(43)}{\sqrt{2} (4)(5)}$$

Assuming $K_d = .955$, then $C_W = .225 C_1$ for three phase delta machines and $C_W = .390 C_1$ for three phase star machines.

(73)

 C_p

POLE CONSTANT - The ratio of the average to the maximum value of the field form. This ratio can be an input or output. For C_p to be an output, insert 0. on input sheet. For C_p to be an input, determine as follows:

For pole heads with more than one radius C_p is calculated from the same field form that was used to determine C_1 , and this method is described in the section titled "Derivations" in the Appendix. For pole heads with only one radius C_p is obtained from Curve #4. Note the correction factor at the top of the curve.

(74)

 C_M

DEMAGNETIZING FACTOR - direct axis - This factor can be an input or output. For C_M to be an output, insert 0. on input sheet. For C_M to be an input, determine as follows:

$$C_M = \frac{(\alpha)\pi + \sin[(\alpha)\pi]}{4 \sin[(\alpha)\pi/2]} = \frac{(77)\pi + \sin[(77)\pi]}{4 \sin[(77)\pi/2]}$$

C_M can also be obtained from Curve 9.

(75)

 C_q

CROSS MAGNETIZING FACTOR - quadrature axis - This factor can be an input or output. For C_q to be an output, insert 0. on input sheet. For C_q to be an input, determine as follows:

$$C_q = \frac{1/2 \cos [(\alpha) \pi/2] + (\alpha) \pi - \sin [(\alpha) \pi]}{4 \sin [(\alpha) \pi/2]}$$

$$= \frac{1/2 \cos [(77) \pi/2] + (77) \pi - \sin [(77) \pi]}{4 \sin [(77) \pi/2]}$$

valid for
concentric
poles

C_q can also be obtained from Curve 9.

(76) -- POLE DIMENSIONS - Locations per Figure 2

b_{p2} = width of pole at edge of stator stack

b_{p1} = width of pole at end

t_{p2} = thickness of pole at edge of stator stack

t_{p1} = thickness of pole at end

ℓ_{co} = length of coil

ℓ_p = length of pole

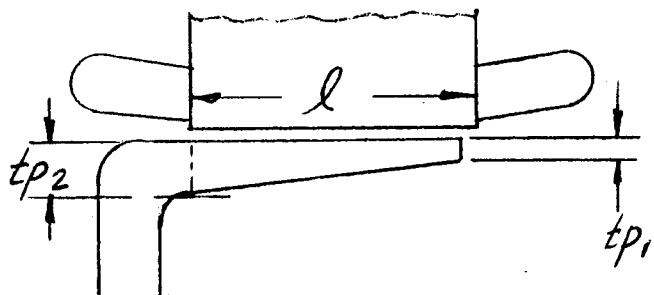
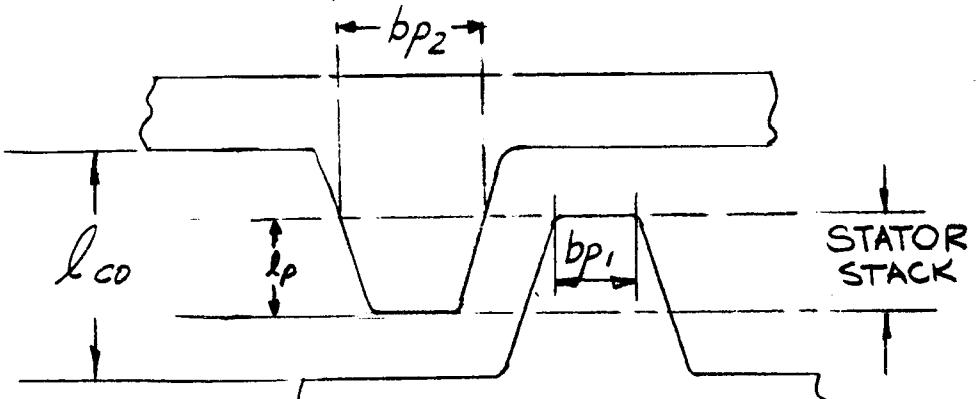


FIG 2

(77)

 \propto POLE EMBRACE -

$$= \frac{(b_{p1}) + (b_{p2})}{2\gamma_p} = (76) + (76) \\ 2(41)$$

(77a)

--

The next 14 items deal with the calculation of rotor and stator leakage permeance. A number of illustrations are included to help identify and locate the actual path. This computer program is set up to handle the permeance calculations two ways.

- 1) P_1 through P_7 can be calculated by the computer.
For this case, insert 0.0 on the input sheet.
- 2) P_1 through P_7 can be calculated by the designer.
For this case, insert the actual calculated value on the input sheet.

Permeance calculations P_1 through P_7 are all based on the equations

$$P = \frac{u \text{ (area)}}{\ell}$$

Where $u = 3.19$

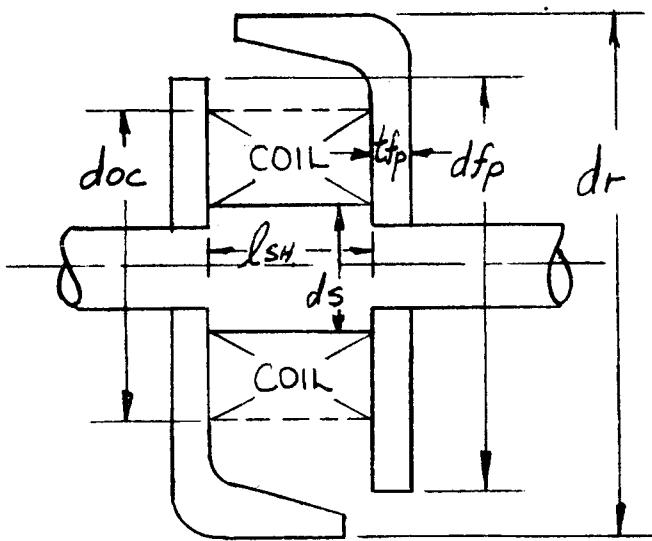
Area = cross-sectional area perpendicular to ℓ
 $=$ length of permeance leakage path

Many of the equations used in this section are taken from Roter's "Electromagnetic Devices". Refer to the supplement at the end of this computer design manual for an explanation of each condition.

(78)

--

ROTOR, COIL AND SHAFT DIMENSIONS - These dimensions are inputs and are required in the calculations that follow:



- ℓ_{sh} = length of shaft (flux carrying portion)
- d_{fp} = diameter of flux plate
- d_r = outside dia. of rotor (also identified in item (lla))
- d_{oc} = outside diameter of coil
- d_s = outside dia. of shaft (flux carrying portion)
- t_{fp} = thickness of flux plate

Figure 3

(79)

 a_p

POLE AREA - The effective cross-sectional area of the pole.

$$a_p = (b_{p2})(t_{p2}) = (76)(76)$$

(80)

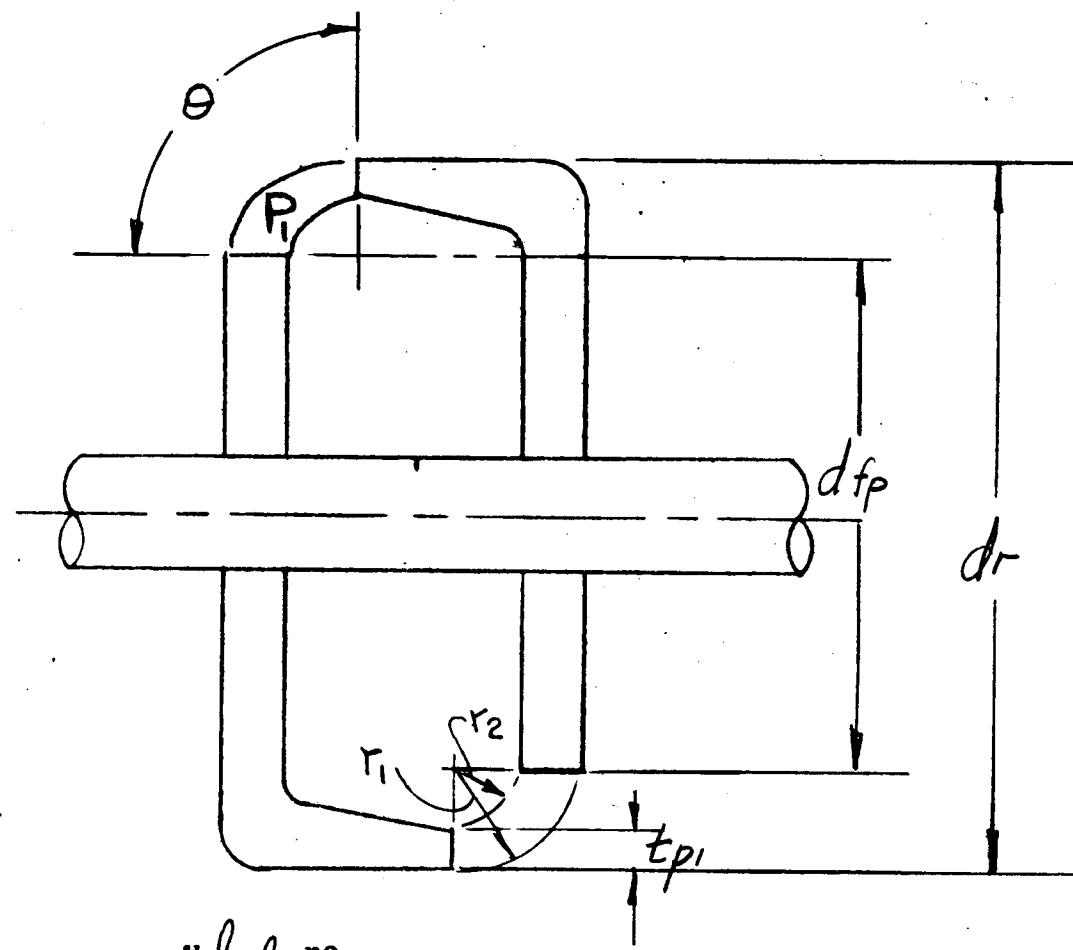
 P_1

POLE HEAD END LEAKAGE - This input can be either 0.0 of the actual value if available. Refer to Item (86) for explanation. See Figure 4 for location.

$$* P_1 = \frac{6.28(b_{p1})}{\pi} \quad \ell_n \frac{r_2}{r_1} = \frac{6.28(76)}{\pi} \quad \ell_n \frac{(80a)}{(80b)}$$

* The formula for P_1 is taken from the supplement at the end of this computer design manual.

P_1 POLE HEAD LEAKAGE



$$P = \frac{\mu l_z}{\theta} \ln \frac{r_2}{r_1}$$

$$r_2 = \frac{d_r - d_{fp}}{2} \quad r_1 = r_2 - t_{p1}$$

$$P_1 = 2 \frac{(3.19)}{\pi} b_{p1} \ln \frac{r_2}{r_1}$$

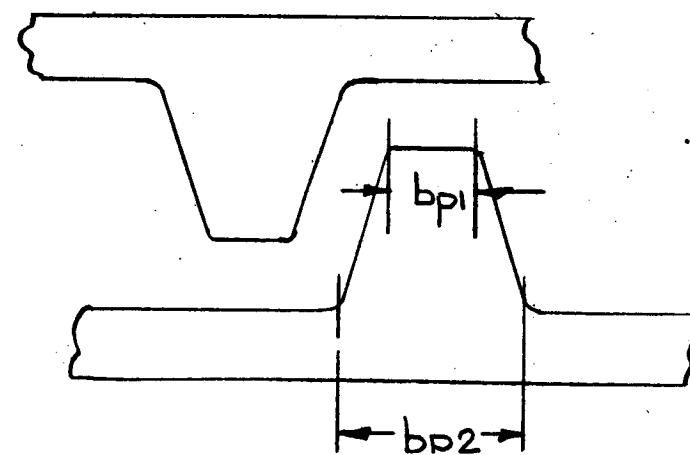


FIG 4

$$(80a) \quad r_2 = \frac{(d_r) - (d_{fp})}{2} = \frac{(l1a) - (78)}{2}$$

$$(80b) \quad r_1 = (r_2) - (t_{pl}) = (80a) - (76)$$

(81) P_2 POLE HEAD SIDE LEAKAGE - This input can be either 0.0 or the actual value if available. Refer to Item (86) for explanation. See Figure 5 for location.

$$P_2 = \frac{3.19 \left\{ (\ell_p) \left[\frac{(t_{p2}) + (t_{pl})}{2} \right] \right\}}{\ell_2} = \frac{3.19 \left\{ (76) \left[\frac{(76) + (76)}{2} \right] \right\}}{(81a)}$$

(81a) ℓ_2 LENGTH OF PERMEANCE PATH 2

$$\ell_2 = \tau_p - \left[\frac{(b_{pl}) + (b_{p2})}{2} \right] = (4l) - \left[\frac{(76) + (76)}{2} \right]$$

(82) P_3 POLE BODY AND LEAKAGE - This input can be either 0.0 or the actual value if available. Refer to Item (77a) for explanation. See Figure 6 for location.

$$*P_3 = \frac{6.28 \left\{ \frac{3(b_{pl}) + (b_{p2})}{4} \right\}}{\pi} \ln \frac{(r_3)}{(r_4)} = \frac{6.28 \left\{ \frac{3(76) + (76)}{4} \right\}}{\pi} \ln (82)$$

*The formula for P_3 is taken from the supplement at the end of this computer design manual.

$$(82a) \quad -- \quad r_3 = (\ell_{co}) - \frac{(\ell_p)}{2} = (76) - \frac{(76)}{2}$$

$$(82b) \quad -- \quad r_4 = (\ell_{co}) - (\ell_p) = (76) - (76)$$

P_2 POLE HEAD SIDE LEAKAGE

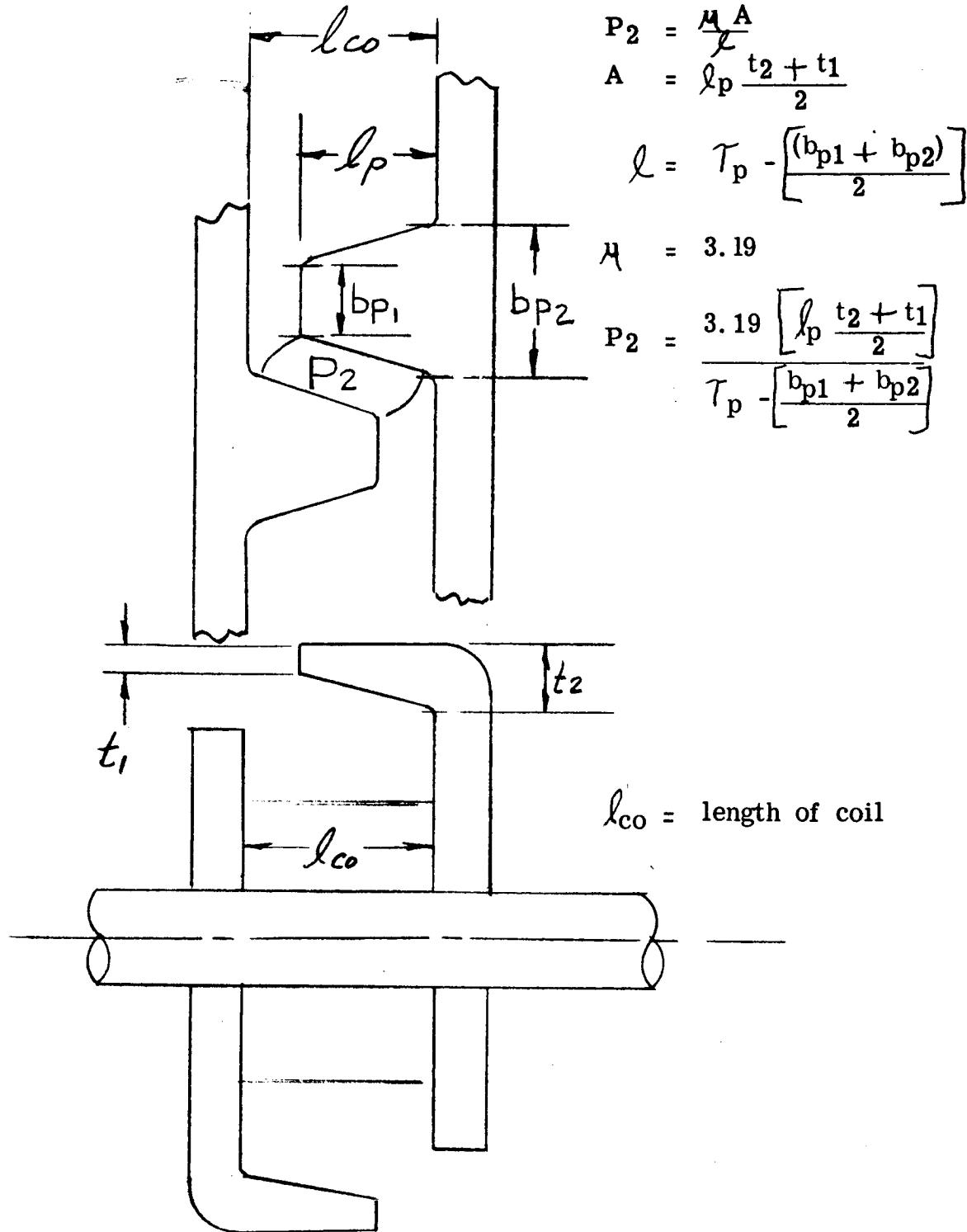
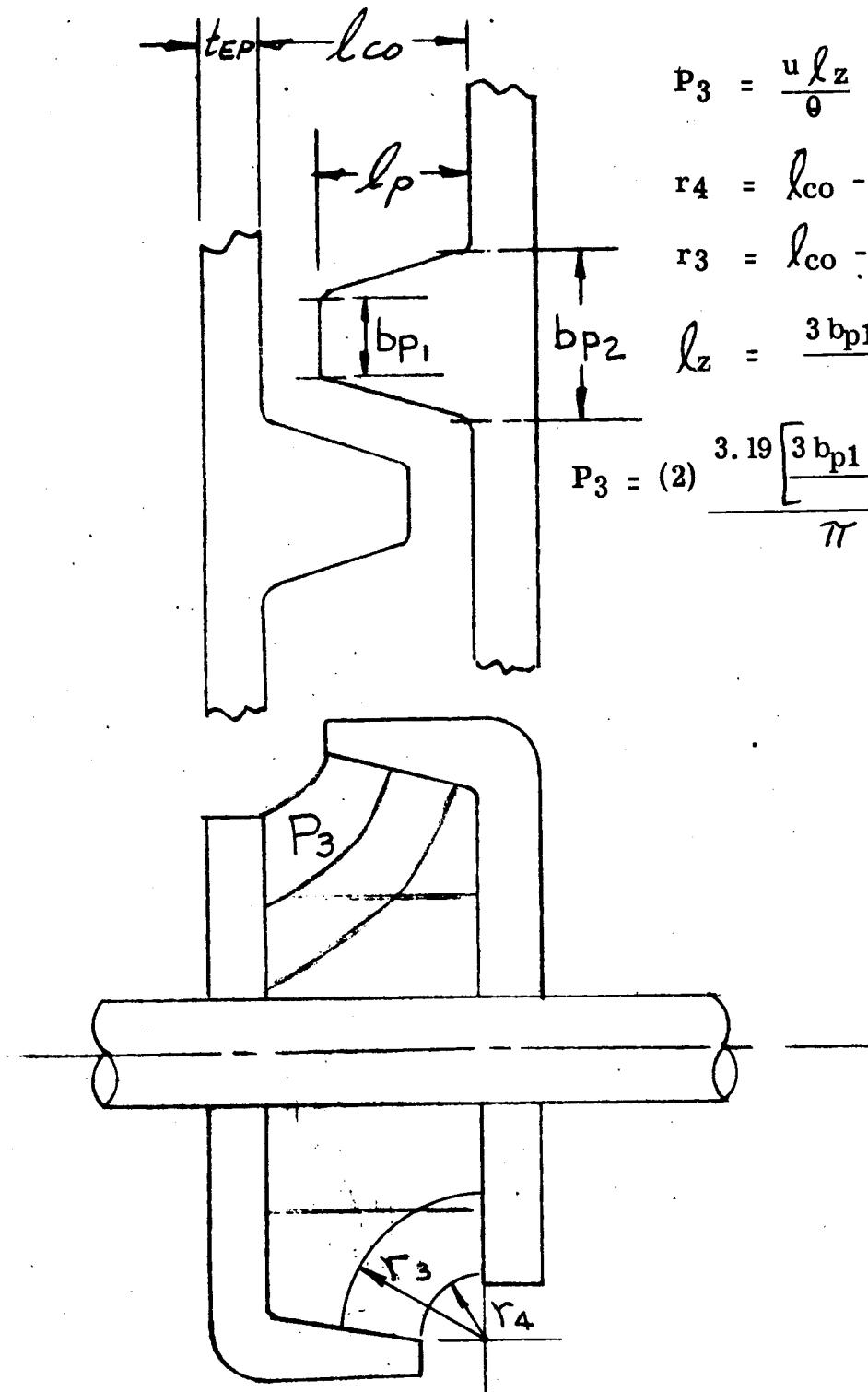


FIG 5

P₃ POLE BODY END LEAKAGE



$$P_3 = \frac{u \ell_z}{\theta} \ell_n \frac{r_3}{r_4}$$

$$r_4 = \ell_{co} - \ell_p$$

$$r_3 = \ell_{co} - \frac{\ell_p}{2}$$

$$\ell_z = \frac{3b_{p1} + b_{p2}}{4}$$

$$P_3 = (2) \frac{3.19 \left[\frac{3b_{p1} + b_{p2}}{4} \right] \ell_n \frac{\ell_{co} - \frac{\ell_p}{2}}{\pi}}{\ell_{co} - \ell_p}$$

FIG 6.

(83) P₄

POLE BODY SIDE LEAKAGE - This input can be either 0.0 or the actual value if available. Refer to Item (77a) for explanation. See Figure 7,8 for location.

When (6) > 4

$$*P_4 = \frac{3.19(\ell_p)}{\pi} \ell_n \left[1 + \frac{(b_{pl}) + (b_{p2})}{(Z)} \right]$$

$$= \frac{3.19(76)}{\pi} \ell_n \left[1 + \frac{(76) + (76)}{(83)} \right]$$

$$\text{Where } (Z) = \tau_p - \left[\frac{(b_{pl}) + (b_{p2})}{2} \right] = (41) - \left[\frac{(76) + (76)}{2} \right]$$

When (6) < 4

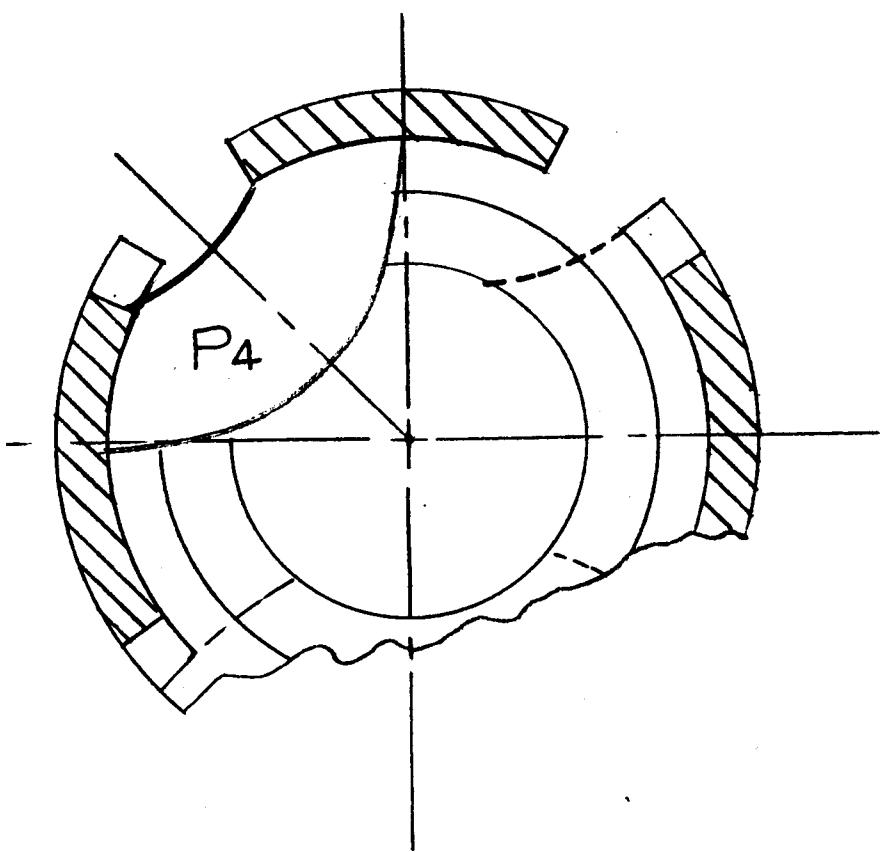
$$*P_4 = \frac{3.19(\ell_p)}{\pi} \frac{3}{2} \ell_n \left[1 + \frac{(b_{pl}) + (b_{p2})}{(Z)} \right]$$

$$= \frac{3.19(76)}{\pi} \frac{3}{2} \ell_n \left[1 + \frac{(76) + (76)}{(83)} \right]$$

* The formula for P₄ is taken from the supplement at the end of this computer design manual.

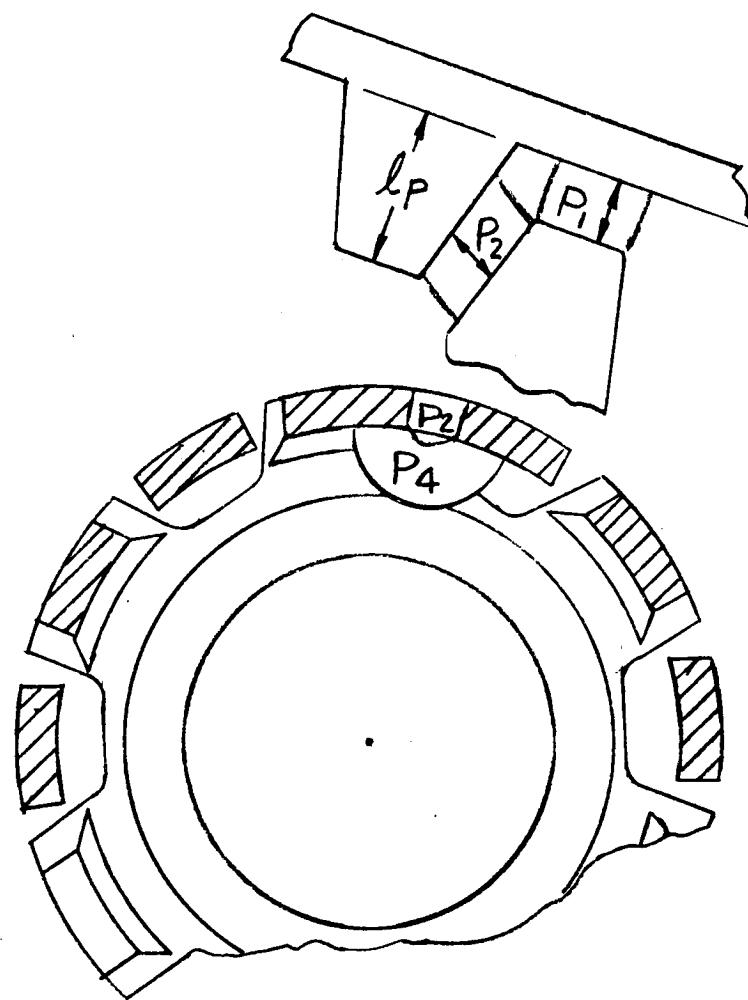
(84) P₅

FIELD COIL LEAKAGE PERMEANCE, ROTOR - This input can be either 0.0 or the actual value if available. Refer to Item (77a) for explanation. See Figure 9 for location.



P₄ IN A FOUR-POLE MACHINE

FIG 7



From Roter's "Electromagnetic Devices", Page 131, Permeance of a Half Annulus.

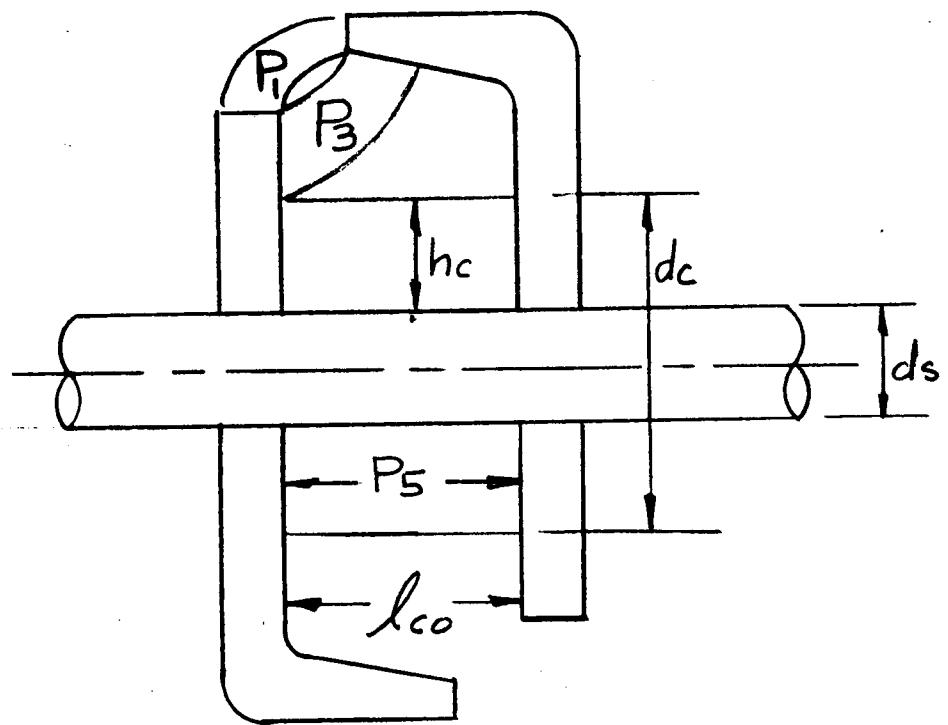
For 6 poles and more:

$$P_4 = \frac{\mu l_p}{\pi} l_n \left[1 + \frac{b_{p1} + b_{p2}}{z} \right]$$

For 4 poles the above formula is too optimistic. Use

$$P_4 = \frac{\mu l_p}{\pi} \frac{3}{2} l_n \left[1 + \frac{b_{p1} + b_{p2}}{z} \right]$$

FIG 8



$$P_5 = \frac{\mu A}{l} = \frac{\mu \pi}{l c o} \left[\frac{d_c^2}{4} - \frac{d_s^2}{4} \right] \frac{2}{3}$$

FIG 9

$$P_5 = \frac{3.19 \pi}{(\ell_{co})} \left[\frac{(d_{co})^2}{4} - \frac{(d_s)^2}{4} \right] \frac{2}{3}$$

$$= \frac{3.19 \pi}{(76)} \left[\frac{(78)^2}{4} - \frac{(78)^2}{4} \right] \frac{2}{3}$$

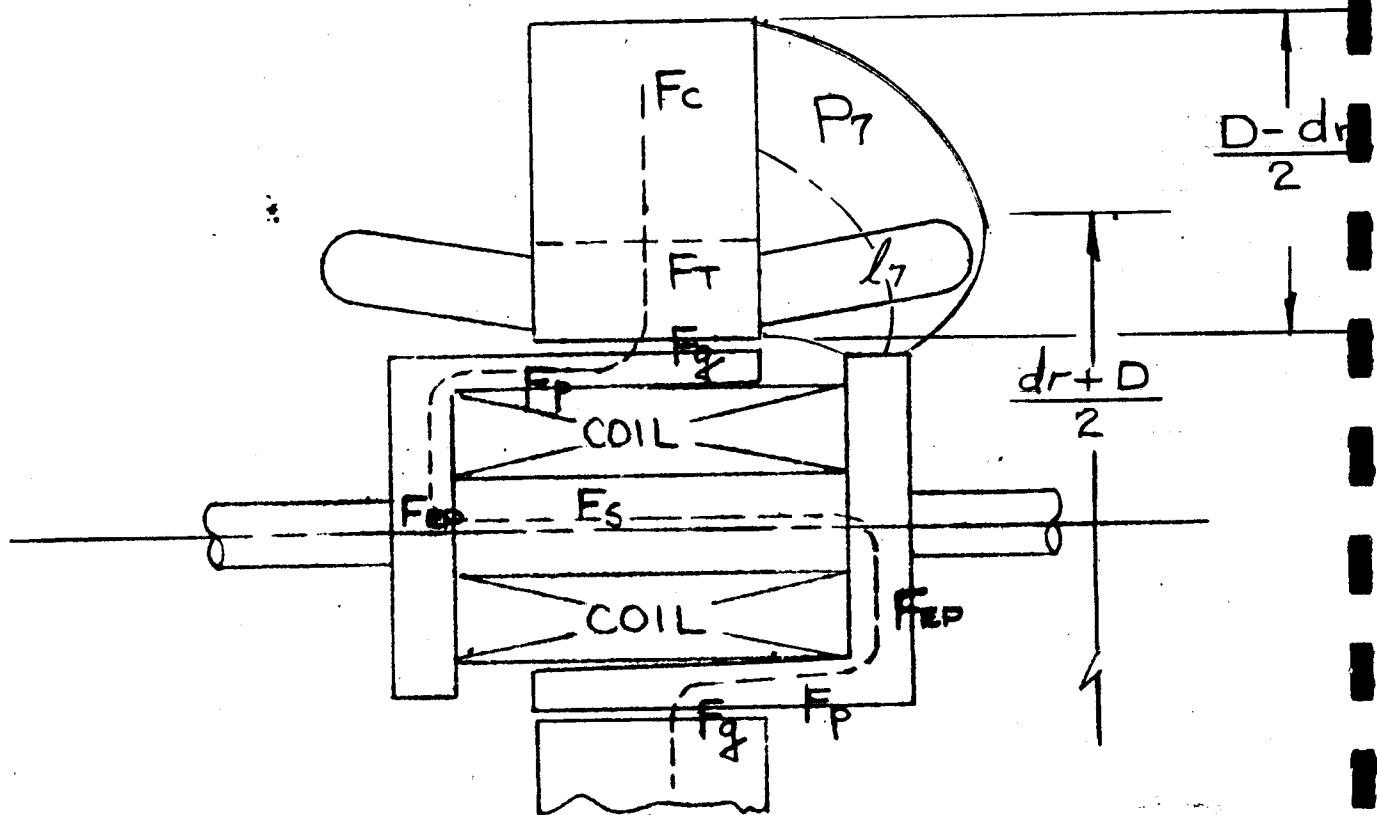
(86) P₇ STATOR TO COIL YOKE LEAKAGE - This input can be either 0.0 or the actual value if available. Refer to Item (77a) for explanation. See Figure 10 for location.

$$P_7 = \frac{3.19 \frac{\pi}{2} \left[\frac{(d_r) + (D)}{2} \right] \left[\frac{(D) - (d_r)}{2} \right] + \pi(d_r)(t_{fp})}{(\ell_7)}$$

$$= \frac{3.19 \frac{\pi}{2} \left[\frac{(lla) + (12)}{2} \right] \left[\frac{(lla) - (12)}{2} \right] + \pi(12)(78)}{(86)}$$

$$\text{Where } \ell_7 = \frac{(D) - (d_r)}{2} = \frac{(12) - (lla)}{2}$$

(87) The next set of calculations deals with the no load saturation. The equations as set up in this section can be used to calculate the complete no load saturation for any voltage. When the no load saturation data is required at various voltages, insert 1. on the input sheet for "no load saturation". The computer will then calculate the complete no load saturation curve at 80, 90, 100, 110, 120, 130, 140, 150 and 160% of rated volts. When the complete saturation data is not necessary, insert 0. on the input sheet and the computer will calculate only the 100% volt data.



$$\text{Area}_7 = \frac{\pi}{2} \frac{(dr + D)}{2} \frac{(D - dr)}{2} + \pi d_r t_{EP}$$

$$\text{Length}_7 = \frac{D - dr}{2} \text{ approx.}$$

$$P_7 = H \left[\frac{\pi}{8} (D^2 - d_r^2) + \frac{\pi d_r t_{EP}}{2} \frac{1}{\frac{D - dr}{4}} \right]$$

$$P_7 = H \left[\frac{\pi}{2} (D + d_r) + \frac{2 \pi d_r t_{EP}}{D - dr} \right] \text{ Each side of stator}$$

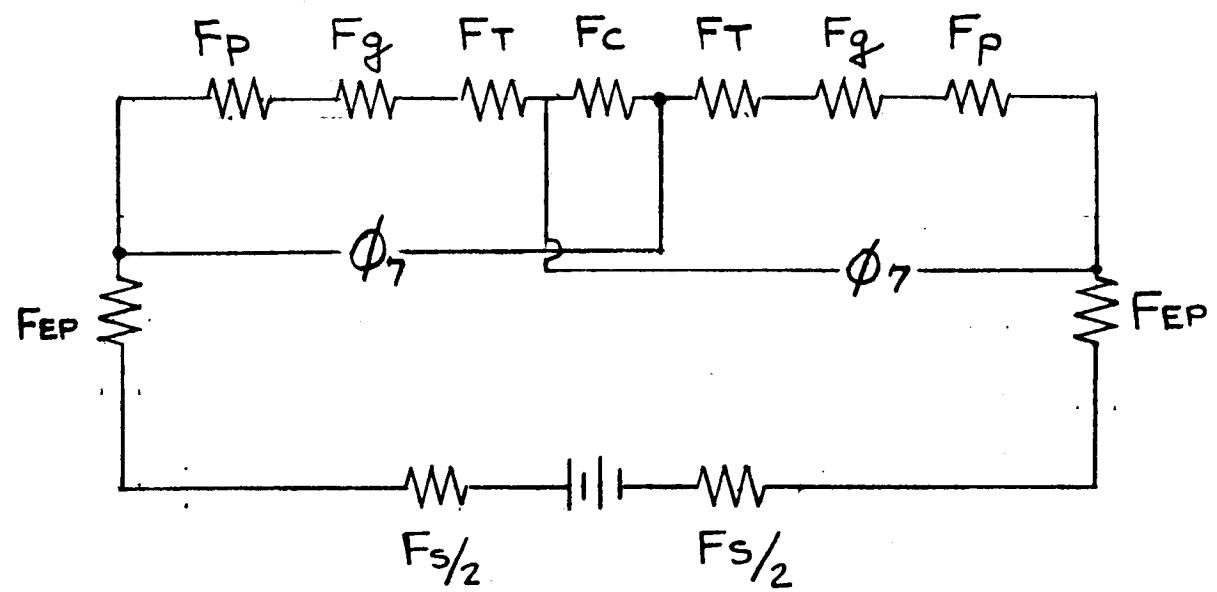
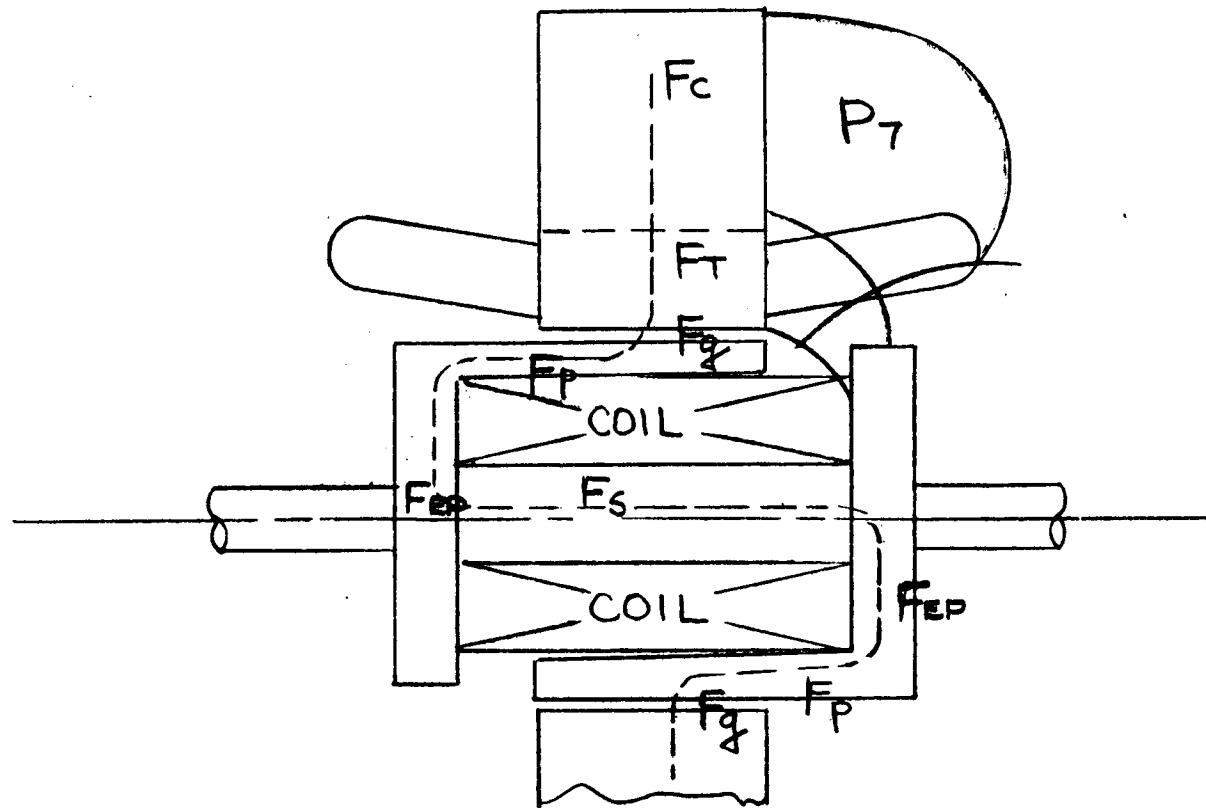


FIG 11

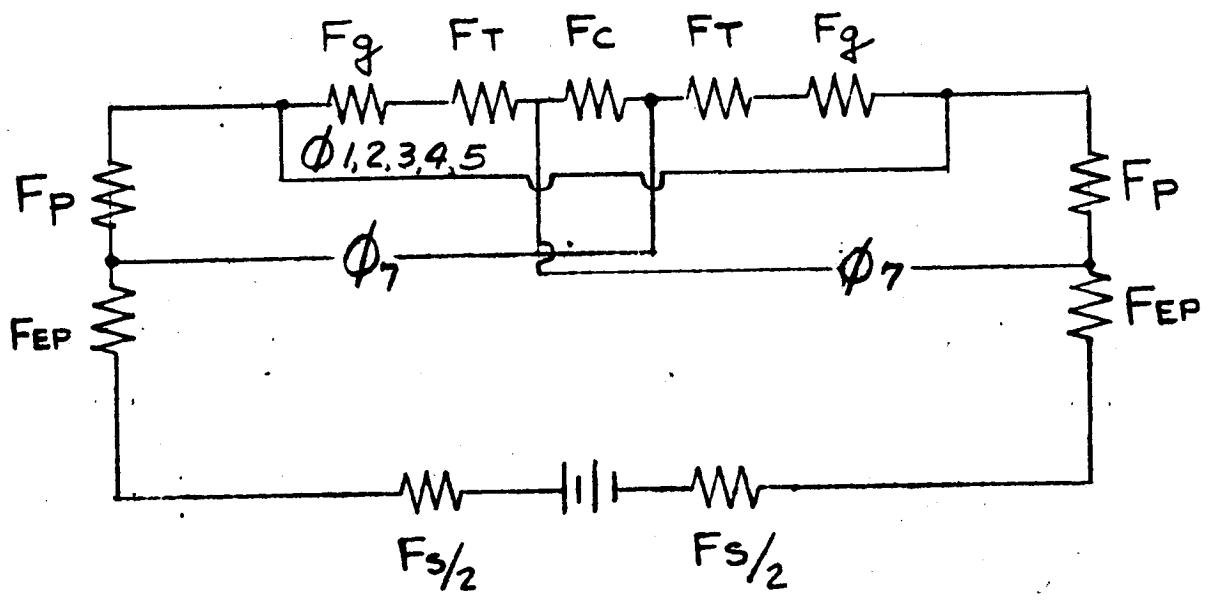
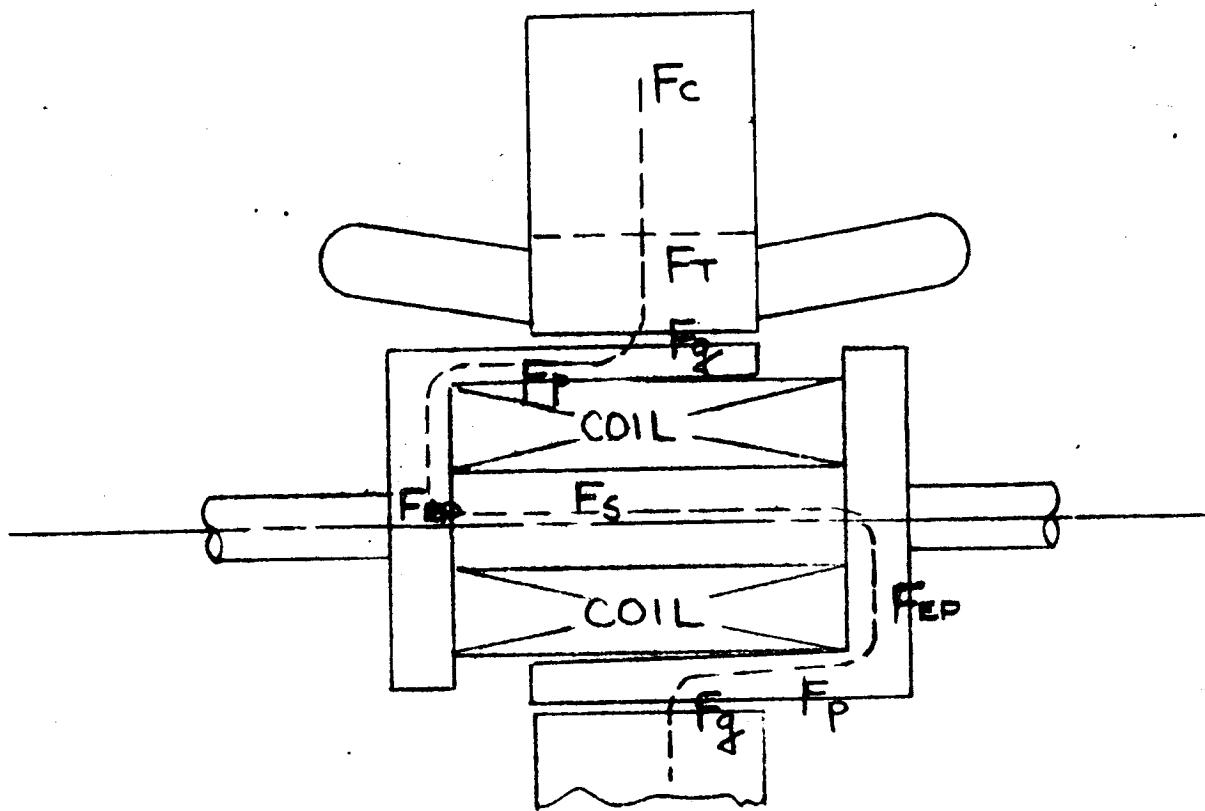


FIG 12

(88)	ϕ_T	<u>TOTAL FLUX</u> in Kilolines
		$\phi_T = \frac{6(E)10^6}{(C_W)(n_e)(RPM)} = \frac{6(3)10^6}{(72)(45)(17)}$
(91)	B_t	<u>TOOTH DENSITY</u> in Kilolines/in ² - The flux density in the stator tooth at 1/3 of the distance from the minimum section.
		$B_t = \frac{\phi_T}{(Q)(\ell_s)(b_t/3)} = \frac{(88)}{(23)(17)(57a)}$
(92)	ϕ_p	<u>FLUX PER POLE</u> in Kilolines
		$\phi_p = \frac{(\phi_T)(C_p)}{(P)} = \frac{(88)(73)}{(6)}$
(94)	B_c	<u>CORE DENSITY</u> in Kilolines/in ² - The flux density in the stator core
		$B_c = \frac{(\phi_p)}{2(h_c)(\ell_s)} = \frac{(92)}{2(24)(17)}$
(95)	B_g	<u>GAP DENSITY</u> in Kilolines/in ² - The maximum flux density in the air gap
		$B_g = \frac{(\phi_T)}{\pi(d)(l)} = \frac{(88)}{\pi(11)(13)}$
(96)	F_g	<u>AIR GAP AMPERE TURNS</u> - The field ampere turns per pole required to force flux across the air gap when operating at no load with rated voltage.
		$F_g = \frac{(B_g)(g_e)}{3.19} = \frac{(95)(69)}{3.19}$

(97)

 F_T STATOR TOOTH AMPERE TURNS

$$F_T = h_s [NI/in at density B_t]$$

= (22) [Look up on stator magnetization curve given
in (18) @ density (91)]

(98)

 F_c STATOR CORE AMPERE TURNS

$$F_c = \left[\frac{\pi(D) - (h_c)}{4(P)} \right] [NI/in @ density of B_c]$$

$$= \left[\frac{\pi(12) - (24)}{4(6)} \right] [Look up on stator magnetization
curve given in (18) @ density (94)]$$

(98a)

 F_s STATOR AMPERE TURNS, total

$$F_s = (F_T) + (F_c) = (97) + (98)$$

(99)

 Q_7 LEAKAGE FLUX FROM THE STATOR TO THE FLUX PLATESAT THE ENDS OF THE ROTOR - The same flux leaks from

the rotor to the stator on one side as leaks out from the stator to the rotor on the other side. This flux does not pass through the air gap but does pass through the rotor shaft and flux plates.

$$Q_7 = (P_7) [(F_p) + (F_g) + (F_T) + (F_c)] \times 10^{-3}$$

$$= (86) [(104) + (96) + (97) + (98)] \times 10^{-3}$$

The items to follow

are to be calculated

for variable loads. The first set of calculations are at no load. These calculations will then be repeated for

100% load. From then on any variation in load would be a repeat of the 100% load calculations with the proper percent load inserted.

(100) ϕ_{ℓ} LEAKAGE FLUX - at no load

$$\begin{aligned}\phi_{\ell} &= (P_e) \left[(F_g) + (F_s) \right] \times 10^{-3} \\ &= (160a) \left[(131) + (130a) \right] \times 10^{-3}\end{aligned}$$

(102) ϕ_{PT} TOTAL FLUX PER POLE - at no load

$$\phi_{PT} = \phi_P + \phi_{\ell} = (92) + (100)$$

(103) B_p POLE DENSITY - The apparent flux density at the base of the pole.

$$B_p = \frac{(\phi_{PT})}{(ap)} = \frac{(102)}{(79)}$$

(104) F_p POLE AMPERE TURNS - at no load. The ampere turns per pole required to force the flux through the pole and flux plate at no load rated voltage. In general the flux plate density is kept fairly low and its ampere turns can be neglected. The no load pole ampere turns per pole are calculated as the product of (ℓ_p) times the NI per inch at the density (Bp). Use magnetization curve submitted per Item (18) for rotor.

$$F_p = (\ell_p) \left[NI/in @ density (B_p) \right]$$

$$= (76) \left[\begin{array}{l} \text{Look up on rotor magnetization curve} \\ \text{given in (18) @ density (103)} \end{array} \right]$$

(111) ϕ_{SH} FLUX IN SHAFT AND END PLATES - at no load.

$$\phi_{SH} = (\phi_{PT}) \frac{(P)}{2} + \phi_7$$

$$= (102) \frac{(6)}{2} + (99)$$

NOTE: No provision is made for calculating the density in the end flux plates. Make the plates thick enough that the periphery of the pole at its base times the thickness of the plate is equal to the cross-sectional area of the pole at its junction with the plate.

(113) B_{SH} FLUX DENSITY OF SHAFT - at no load.

$$B_{SH} = \frac{(\phi_{SH})}{a_s} = \frac{(111)}{(113)}$$

$$\text{Where } a_s = \frac{\pi(d_s)^2}{4} = \frac{\pi(78)^2}{4}$$

(114) F_{SH} AMPERE TURNS DROP IN SHAFT AT B_S

$$F_{SH} = I_{SH} \left[NI/\text{in} @ \text{density } (B_{SH}) \right]$$

$$= (78) \left[\begin{array}{l} \text{Look up on shaft magnetization curve} \\ \text{given in (18) at density (113)} \end{array} \right]$$

(127) F_{NL} TOTAL AMPERE TURNS - at no load. The total ampere turns per pole required to produce rated voltage at no load.

$$F_{NL} = \left[2(F_g) + 2(F_S) + 2(F_P) + (F_{SH}) \right] = \left[(96) + (98a) + (104) + (114) \right]$$

(127a)	I_{FNL}	<u>FIELD CURRENT</u> - at no load.
		$I_{FNL} = (F_{NL})/(N_p) = (127)/(146)$
(127b)	E_{FNL}	<u>FIELD VOLTS</u> - at no load. This calculation is made with cold field resistance at 20°C for no load condition.
		$E_F = (I_{FNL})(R_f \text{ cold}) = (127a)(154)$
(127c)	S_F	<u>CURRENT DENSITY</u> - at no load. Amperes per square inch of field conductor.
		$S_F = (I_{FNL})/(a_{cf}) = (127)/(153)$
(128)	A	<u>AMPERE CONDUCTORS</u> per inch - The effective ampere conductors per inch of stator periphery. This factor indicates the "specific loading" of the machine. Its value will increase with the rating and size of the machine and also will increase with the number of poles. It will decrease with increases in voltage or frequency. A is generally higher in single phase machines than in polyphase ones.
		$A = \frac{(I_{PH})(n_s)(K_p)}{(C)(\tau_s)} = \frac{(8)(30)(44)}{(32)(26)}$
(129)	X	<u>REACTANCE FACTOR</u> - The reactance factor is the quantity by which the specific permeance must be multiplied to give percent reactance. It is the percent reactance for unit specific permeance, or the percent of normal voltage induced by a fundamental flux per pole per inch numerically equal to the fundamental armature ampere turns at rated current. Specific permeance

is defined as the average flux per pole per inch of core length produced by unit ampere turns per pole.

$$X = \frac{100(A)(K_d)}{\sqrt{2} (C_1)(B_g) \times 10^3} = \frac{100(128)(43)}{\sqrt{2} (71)(125) \times 10^3}$$

- (130) X_ℓ LEAKAGE REACTANCE - The leakage reactance of the stator for steady state conditions. When (5) = 3, calculate as follows:

$$X_\ell = X [(\lambda_i) + (\lambda_E)] = (129) [(62) + (64)]$$

In the case of two phase machines a component due to belt leakage must be included in the stator leakage reactance. This component is due to the harmonics caused by the concentration of the MMF into a small number of phase belts per pole and is negligible for three phase machines. When (5) = 2, calculate as follows:

$$\lambda_B = \frac{0.1(d)}{(P)(g_e)} \left[\frac{\sin \left[\frac{3(y)}{(m)(q)} \right] 90^\circ}{(K_p)} \right] = \frac{0.1(11)}{(6)(69)} \left[\frac{\sin \left[\frac{3(31)}{(5)(25)} \right] 90^\circ}{(44)} \right]$$

$$X_\ell = X [(\lambda_i) + (\lambda_E) + (\lambda_B)] \text{ where } \lambda_B = 0 \text{ for 3 phase machine}$$

$$X_\ell = (79) [(62) + (64) + (80)]$$

(131)	X_{ad}	<u>REACTANCE - direct axis</u> - This is the fictitious reactance due to armature reaction in the direct axis.
		$X_{ad} = (X)(\lambda_a)(C_1)(C_M) = (129)(70)(71)(74)$
(132)	X_{aq}	<u>REACTANCE - quadrature axis</u> - This is the fictitious reactance due to armature reaction in the direct axis.
		$X_{aq} = (X)(C_q)(\lambda_a) = (129)(75)(70)$
(133)	X_d	<u>SYNCHRONOUS REACTANCE - direct axis</u> - The steady state short circuit reactance in the direct axis.
		$X_d = (X_\rho) + (X_{ad}) = (130) + (131)$
(134)	X_q	<u>SYNCHRONOUS REACTANCE - quadrature axis</u> - The steady state short circuit reactance in the quadrature axis.
		$X_q = (X_\rho) + (X_{aq}) = (130) + (132)$
(145)	V_r	<u>PERIPHERAL SPEED</u> - The velocity of the rotor surface in feet per minute
		$V_r = \frac{\pi(d_r)(RPM)}{12} = \frac{\pi(la)(7)}{12}$
(146)	N_F	<u>NUMBER OF FIELD TURNS</u>
(147)	ℓ_{tF}	<u>MEAN LENGTH OF FIELD TURN</u>
(148)	--	<u>FIELD CONDUCTOR DIA OR WIDTH</u> in inches
(149)	--	<u>FIELD CONDUCTOR THICKNESS</u> in inches - Set this item = 0. for round conductor.

(150)	$X_f^{\circ}\text{C}$	<u>FIELD TEMP IN $^{\circ}\text{C}$</u> - Input temp at which full load field loss is to be calculated.
(151)	ρ_f	<u>RESISTIVITY</u> of field conductor @ 20°C in micro ohm-inches. Refer to table given in item (51) for conversion factors.
(152)	ρ_f (hot)	<u>RESISTIVITY</u> of field conductor at $X_f^{\circ}\text{C}$ $\rho_f \text{ (hot)} = \rho_f \left[\frac{(X_f^{\circ}\text{C}) + 234.5}{254.5} \right] = (104) \left[\frac{(150) + 234.5}{254.5} \right]$
(153)	a_{cf}	<u>CONDUCTOR AREA OF FIELD WINDING</u> - Calculate same as stator conductor area (46) except substitute (149) for (39) (148) for (33)
(154)	R_f (cold)	<u>COLD FIELD RESISTANCE @ 20°C</u> $R_f \text{ (cold)} = (\rho_f) \frac{(N_f) (l_{tf})}{(a_{cf})} = (151) \frac{(146) (147)}{(153)}$
(155)	R_f (hot)	<u>HOT FIELD RESISTANCE</u> - Calculated at $X_f^{\circ}\text{C}$ (103) $R_f \text{ (hot)} = (\rho_f \text{ hot}) \frac{(N_f) (l_{tf})}{(a_{cf})} = (152) \frac{(146) (147)}{(153)}$
(156)	--	<u>WEIGHT OF FIELD COIL</u> in lbs. $\# \text{ of copper} = .321(N_f)(l_{tf})(a_{cf})$ $= .321(146)(6)(147)(153)$ ALSO REFER TO NOTE GIVEN IN ITEM (65)

(157) -- WEIGHT OF ROTOR IRON - Because of the large number of different pole shapes, one standard formula cannot be used for calculating rotor iron weight. Therefore, the computer will not calculate rotor iron weight. The space is allowed on the input sheet for record purposes only. By inserting 0. in the space allowed for rotor iron weight, the computer will show "0". on the output sheet. If the rotor iron weight is available and inserted on input sheet, then the output sheet will show this same weight on the output sheet.

(160) X_F FIELD LEAKAGE REACTANCE

$$X_F = (X_{ad}) \left[1 - \frac{[(C_1)/(C_m)]}{2(C_p) + \frac{4(\lambda_F)}{\pi(\lambda_a)}} \right]$$

$$= (81) \left[1 - \frac{[(71)/(74)]}{2(73) + \frac{4(160c)}{\pi(70)}} \right]$$

(160a) P_e ROTOR LEAKAGE PERMEANCE

$$P_e = P [P_1 + P_2 + P_3 + P_4] + P_5$$

$$= (6) [(80) + (81) + (82) + (83)] + (84)$$

(160c) λ_F ROTOR LEAKAGE PERMEANCE per inch of stator stack

$$\lambda_F = \frac{P_e}{\ell} = \frac{(160a)}{(13)}$$

(161) L_f FIELD SELF INDUCTANCE

$$L_f = (N_f)^2 \ell_p \left[(C_P)(\lambda_a) \frac{\pi}{2} + (\lambda_f) \right] \times 10^{-8}$$

$$= (99)^2 (76) \left[(73)(70) \frac{\pi}{2} + (160c) \right] \times 10^{-8}$$

(166)

 X'_{du} UNSATURATED TRANSIENT REACTANCE

$$X'_{du} = (X_f) + (X_f) = (130) + (160)$$

(167)

 X'_d SATURATED TRANSIENT REACTANCE

$$X'_d = .88(X'_{du}) = .88(166)$$

(168)

 X''_d SUBTRANSIENT REACTANCE in direct axis

$$X''_d = (X'_d) = (167)$$

(169)

 X''_q SUBTRANSIENT REACTANCE in quadrature axis

$$X''_q = (X_q) = (134)$$

(170)

 X_2

NEGATIVE SEQUENCE REACTANCE - The reactance due to the field which rotates at synchronous speed in a direction opposite to that of the rotor.

$$X_2 = .5 [X''_d + X''_q] = .5 [(168) + (169)]$$

(172)

 X_0

ZERO SEQUENCE REACTANCE - The reactance drop across any one phase (star connected) for unit current in each of the phases. The machine must be star connected for otherwise no zero sequence current can flow and the term then has no significance.

If $(28) = 0$, then $X_0 = 0$

If $(28) \neq 0$, then

$$X_o = X \left\{ \frac{(K_{x0})}{(K_{x1})} \left[(\lambda_i) + (\lambda_{Bo}) \right] + \frac{1.667 \left[(h_1) + 3(h_3) \right]}{(m)(q)(K_p)^2(K_d)^2(b_s)} + .2(\lambda_E) \right\}$$

$$= (79) \left\{ \frac{(173)}{(174)} \left[(62) + (123c) \right] + \frac{1.667 \left[(22) + 3(22) \right]}{(5)(25)(44)^2(43)^2(22)} + .2(6) \right\}$$

(173) K_{x0} If $(30) = 1$ Then $K_{x0} = 1$

$$\begin{aligned} \text{If } (30) \neq 1 & \quad \text{Then } K_{x0} = \frac{3(y)}{(m)(q)} - 2 \\ & = \frac{3(31)}{(5)(25)} - 2 \end{aligned}$$

(174) K_{x1} If $(30) = 1$ Then $K_{x1} = 1$

If $(30) \neq 1$ Then:

$$K_{x1} = \left[\frac{3(y)}{4(m)(q)} + \frac{1}{4} \right] = \left[\frac{3(31)}{4(5)(25)} + \frac{1}{4} \right] \quad \text{If } (31a) \geq .667$$

$$K_{x1} = \left[\frac{3(y)}{4(m)(q)} - \frac{1}{4} \right] = \left[\frac{3(31)}{4(5)(25)} - \frac{1}{4} \right] \quad \text{If } (31a) < .667$$

(175) λ_{Bo} $\lambda_{Bo} = \frac{(K_{x0})}{(K_p)^2} \left[.07(\lambda_a) \right] = \frac{(173)}{(44)^2} \left[.07(70) \right]$

(176) T'_{do} OPEN CIRCUIT TIME CONSTANT - The time constant of the field winding with the stator open circuited and with negligible external resistance and inductance in the field circuit. Field Resistance at room temperature (20°C) is used in this calculation.

$$T'_{do} = \frac{L_F}{R_F} = \frac{(161)}{(154)}$$

(177)	T_a	<u>ARMATURE TIME CONSTANT</u> - Time constant of the D.C. component. In this calculation stator resistance at room temperature (20°C) is used.
		$T_a = \frac{X_2}{200\pi(f)(r_a)} = \frac{(170)}{200\pi(5a)(177)}$
		Where $r_a = \frac{(m)(I_{PH})^2(R_{SPH} \text{ cold})}{\text{Rated KVA} \times 10^3} = \frac{(5)(8)^2(53)}{(2) \times 10^3}$
(178)	T'_d	<u>TRANSIENT TIME CONSTANT</u> - The time constant of the transient reactance component of the alternating wave.
		$T'_d = \frac{(X'_d)}{(X_d)} (T'_{do}) = \frac{(167)}{(133)} (176)$
(179)	T''_d	<u>SUBTRANSIENT TIME CONSTANT</u> - The time constant of the subtransient component of the alternating wave. This value has been determined empirically from tests on large machines. Use following values: $T''_d = .035 \text{ second at 60 cycle}$ $T''_d = .005 \text{ second at 400 cycle}$
(180)	F_{SC}	<u>SHORT CIRCUIT AMPERE TURNS</u> - The field ampere turns required to circulate rated stator current when the stator is short circuited. $F_{SC} = (X_d)(F_g) = (133)(96)$

(181)	SCR	<u>SHORT CIRCUIT RATIO</u> - The ratio of the field current to produce rated voltage on open circuit to the field current required to produce rated current on short circuit. Since the voltage regulation depends on the leakage reactance and the armature reaction, it is closely related to the current which the machine produces under short circuit conditions and, therefore, is directly related to the SCR.
(182)	I^2R_F	<u>FIELD I^2R</u> - at no load. The copper loss in the field winding is calculated with cold field resistance at 20°C for no load condition.
(183)	F&W	<u>FRICTION & WINDAGE LOSS</u> - The best results are obtained by using existing data. For ratioing purposes, the loss can be assumed to vary approximately as the 5/2 power of the rotor diameter and as the 3/2 power of the RPM. When no existing data is available, the following calculation can be used for an approximate answer. Insert 0. when computer is to calculate F&W. Insert actual F&W when available. Use same value for all load conditions.

$$F\&W = 2.52 \times 10^{-6} (d_r)^{2.5} (\ell_h) (RPM)^{1.5}$$

$$= 2.52 \times 10^{-6} (l_{la})^{2.5} (76) (7)^{1.5}$$

- (184) W_{TNL} STATOR TEETH LOSS - at no load. The no load loss (W_{TNL}) consists of eddy current and hysteresis losses in the iron. For a given frequency the no load tooth loss will vary as the square of the flux density.
- $$W_{TNL} = .453(b_t 1/3)(Q)(\mathcal{J}_s)(h_s)(K_Q)$$
- $$= .453(57a)(23)(17)(22)(184)$$
- $$\text{Where } K_Q = (k) \left[\frac{(B_t)}{(B)} \right]^2 = (19) \left[\frac{(91)}{(20)} \right]^2$$
- (185) w_c STATOR CORE LOSS - The stator core losses are due to eddy currents and hysteresis and do not change under load conditions. For a given frequency the core loss will vary as the square of the flux density (B_c).
- $$w_c = 1.42 \left[(D) - (h_c) \right] (h_c)(\mathcal{J}_s)(K_Q)$$
- $$= 1.42 \left[(12) - (24) \right] (24)(17)(185)$$
- $$\text{Where } K_Q = (k) \left[\frac{(B_c)}{(B)} \right]^2 = (19) \left[\frac{(94)}{(20)} \right]^2$$
- (186) W_{NPL} POLE FACE LOSS - at no load. The pole surface losses are due to slot ripple caused by the stator slots. They depend upon the width of the stator slot opening, the air gap, and the stator slot ripple frequency. The no load pole face loss (W_{PNL}) can be obtained from Graph 2. Graph 2 is plotted on the bases of open

slots. In order to apply this curve to partially open slots, substitute b_0 for b_s . For a better understanding of Graph 2, use the following sample:

K_1 as given on Graph 2 is derived empirically and depends on lamination material and thickness. Those values given on Graph 2 have been used with success. K_1 is an input and must be specified. See Item (187) for values of K_1 .

K_2 is shown as being plotted as a function of $(B_G)^{2.5}$. Also note that upper scale is to be used. Another note in the lower right hand corner of graph indicates that for a solid line (_____), the factor is read from the left scale, and for a broken or dashed line (_____-_____), the right scale should be read.

For example, find K_2 when $B_G = 30$ kilolines. First locate 30 on upper scale. Read down to the intersection of solid line plot of $K_2 = f(B_G)^{2.5}$. At this intersection read the left scale for K_2 . $K_2 = .28$.

Also refer to Item (188) for K_2 calculations.

K_3 is shown as a solid line plot as a function of $(F_{SLT})^{1.65}$. The note on this plot indicates that the upper scale X 10 should be used. Note F_{SLT} = slot frequency. For an example, find K_3 when $F_{SLT} = 1000$. Use upper scale X 10 to locate 1000. Read down to intersection of solid line plot of $K_3 = f(F_{SLT})^{1.65}$. At this intersection read the left scale

for K_3 . $K_3 = 1.35$. Also refer to Item (189) for K_3 calculations.

For K_4 use same procedure as outlined above except use lower scale. Do not confuse the dashed line in this plot with the note to use the right scale. The note does not apply in this case. Read left scale. Also refer to Item (190) for K_4 calculations.

For K_5 use bottom scale and substitute b_0 for b_s when using partially closed slot. Read left scale when using solid plot. Use right scale when using dashed plot. Also refer to Item (191) for K_5 calculations.

For K_6 use the scale attached for C_1 and read K_6 from left scale. Also refer to Item (192) for K_6 calculations.

The above factors (K_2), (K_3), (K_4), (K_5), (K_6) can also be calculated as shown in (188), (189), (190), (191), (192) respectively.

$$W_{PNL} = \pi(d)(A)(K_1)(K_2)(K_3)(K_4)(K_5)(K_6)$$

$$= \pi(11)(13)(187)(188)(189)(180)(199)(192)$$

- (187) K_1 K_1 is derived empirically and depends on lamination material and thickness. The values used successfully for K_1 are shown on Graph 2. They are:

K_1 = 1.17 for .028 lam thickness, low carbon steel
 = 1.75 for .063 lam thickness, low carbon steel
 = 3.5 for .125 lam thickness, low carbon steel
 = 7.0 for solid core

K_1 is an input and must be specified on input sheet.

- (188) K_2 K_2 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

$$K_2 = f(B_G) = 6.1 \times 10^{-5} (B_G)^{2.5}$$

$$= 6.1 \times 10^{-5} (95)^{2.5}$$

- (189) K_3 K_3 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

$$K_3 = f(F_{SLT}) = 1.5147 \times 10^{-5} (F_{SLT})^{1.65}$$

$$= 1.5147 \times 10^{-5} (189)^{1.65}$$

Where $F_{SLT} = \frac{(RPM)}{60} (Q)$

$$= \frac{(7)}{60} (23)$$

- (190) K_4 K_4 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

For $\gamma_s < .9$

$$K_4 = f(\gamma_s) = .81(\gamma_s)^{1.285}$$

$$= .81(26)^{1.285}$$

For $.9 \leq \tau_s \leq 2.0$

$$K_4 = f(\tau_s) = .79(\tau_s)^{1.145}$$

$$= .79(26)^{1.145}$$

For $\tau_s > 2.0$

$$K_4 = f(\tau_s) = .92(\tau_s)^{.79}$$

$$= .92(26)^{.79}$$

- (191) K_5 can be obtained from Graph 2 (see item 186 for explanation of Graph 2) or it can be calculated as follows:
- For $(b_s)/(g) = 1.7$

$$K_5 = f(b_s/g) = .3 \left[(b_s)/(g) \right]^{2.31}$$

$$= .3 \left[(22)/(59) \right]^{2.31}$$

NOTE: For partially open slots substitute b_o for b_s in equations shown.

For $1.7 < (b_s)/(g) \leq 3$

$$K_5 = f(b_s)/(g) = .35 \left[(b_s)/(g) \right]^2$$

$$= .35 \left[(22)/(59) \right]^2$$

For $3 < (b_s)/(g) \leq 5$

$$K_5 = f(b_s)/(g) = .625 \left[(b_s)/(g) \right]^{1.4}$$

$$= .625 \left[(22)/(59) \right]^{1.4}$$

For $(b_S)/(g) > 5$

$$K_5 = f(b_S)/(g) = 1.38 \left[(b_S)/(g) \right]^{.965}$$

$$= 1.38 \left[(22)/(59) \right]^{.965}$$

- (192) K_6 K_6 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

$$K_6 = f(C_1) = 10 \left[.9323(C_1) - 1.60596 \right]$$

$$= 10 \left[.9323(71) - 1.60596 \right]$$

- (194) I^2R STATOR I^2R - at no load. This item = 0. Refer to Item (245) for 100% load stator I^2R .

- (195) -- EDDY LOSS - at no load. This item = 0. Refer to Item (246) for 100% load eddy loss.

- (196) -- TOTAL LOSSES - at no load. Sum of all losses.

$$\begin{aligned} \text{Total losses} &= (\text{Field } I^2R) + (\text{F&W}) + (\text{Stator Teeth Loss}) \\ &\quad + (\text{Stator Core Loss}) + (\text{Pole Face Loss}) \\ &= (182) + (183) + (184) + (185) + (186) \end{aligned}$$

NOTE: The output sheet shows the next items to be: (Rating), (Rating + Losses), (% Losses), (% Efficiency). These items do not apply to the no load calculation since the rating is zero. Refer to Items (175), (176), (177), (178) for these calculations under load.

The no load calculations should all be repeated now for 100% load.

(196a) $\phi_{\ell\ell}$ LEAKAGE FLUX PER POLE at 100% load

$$\begin{aligned}\phi_{\ell\ell} &= \phi_{\ell} \left\{ \frac{(e_d)(F_g) + [1 + \cos(\theta)] (F_T) + (F_C)}{(F_g) + (F_T) + (F_C)} \right\} \\ &= (100) \left\{ \frac{(198)(96) + [1 + \cos(198a)] (97) + (98)}{(96) + (97) + (98)} \right\}\end{aligned}$$

(198) e_d

$$\text{Where } e_d = \cos \psi + (X_d) \sin \psi$$

$$= \cos (198a) + (83) \sin (198a)$$

(198a) θ

$$\text{Where } \theta = \cos^{-1} [\text{Power Factor}]$$

$$= \cos^{-1} [9]$$

$$\begin{aligned}\text{Where } \psi &= \tan^{-1} \left[\frac{\sin(\theta) + (X_q) / (100)}{\cos(\theta)} \right] \\ &= \tan^{-1} \left[\frac{\sin(198a) + (134) / (100)}{\cos(198a)} \right]\end{aligned}$$

$$\text{Where } \psi = \psi - \theta = (198a) - (198a)$$

(207) ϕ_{7L} STATOR TO ROTOR FLUX LEAKAGE at full load.

$$\begin{aligned}\phi_{7L} &= (P_7) \left[(e_d)(F_g) + (F_{PL}) + (F_T) [1 + (\cos \theta)] + (F_C) \right] \\ &= (86) \left[(198)(96) + (213c) + (97) [1 + (9)] + (98) \right] X 10^6\end{aligned}$$

(213) ϕ_{PL} FLUX PER POLE at 100% load

For P.F. 0 to .95

$$\begin{aligned}\phi_{PL} &= (\phi_P) \left[(e_d) - \frac{.93(X_{ad})}{100} \sin(\psi) \right] \\ &= (92) \left[(198a) - \frac{.93(13l)}{100} \sin(198a) \right]\end{aligned}$$

		For P.F. .95 to 1.0
		$\Phi_{PL} = (\Phi_P)(K_C) = (126)(9a)$
(213a)	Φ_{PTL}	<u>TOTAL FLUX PER POLE</u> at 100% load
		$\Phi_{PTL} = \Phi_{PL} + \Phi_{LL} = (213) + (196a)$
(213b)	B_{PL}	<u>FLUX DENSITY AT BASE OF POLE</u> at 100% load
		$B_{PL} = \frac{\Phi_{PTL}}{a_p} = \frac{(213a)}{(79)}$
(213c)	F_{PL}	<u>AMPERE TURNS PER POLE</u> at 100% load
		$F_{PL} = I_p \left[NI/in @ density (B_{PL}) \right]$
		$= (76) \left[\begin{array}{l} \text{Look up ampere turns/inch on rotor} \\ \text{magnetization curve given in (18) at} \\ \text{density (213b)} \end{array} \right]$
(231a)	Φ_{SHL}	$= \Phi_{PTL} \frac{P}{2} + \Phi_{7L} = (162) \frac{(6)}{2} + (207)$
(232)	B_{SHL}	<u>SHAFT FLUX DENSITY</u> at full load.
		$B_{SL} = \frac{(\Phi_{SHL})}{(a_s)} = \frac{(23lb)}{(113)}$
(233)	F_{SHL}	<u>AMPERE TURN DROP IN SHAFT</u> at full load
		$F_{SHL} = I_{SH} \left[\begin{array}{l} NI/in on shaft magnetization curve at \\ \text{density (B}_{SHL}\text{)} \end{array} \right]$
		$= (78) \left[\begin{array}{l} \text{Look up on shaft magnetization curve} \\ \text{given in (18) at density (232)} \end{array} \right]$

(236)	F_{FL}	<u>TOTAL AMPERE TURNS PER POLE</u> at 100% load - The total ampere turns per pole required to produce rated load
		$F_{FL} = 2 \left[(e_d)(F_g) + [1 + (\cos \theta)](F_T) + (F_c) + (F_{PL}) \right] + (F_{SHL})$ $= 2 \left[(198)(96) + [1 + (9)](97) + (98) + (213c) \right] + (233)$
(237)	I_{FFL}	<u>FIELD CURRENT</u> at 100% load
		$I_{FFL} = (F_{FL})/(N_F) = (236)/(146)$
(239)	--	<u>CURRENT DENSITY</u> at 100% load
		Current Density = $(I_{FFL})/(a_{cf}) = (237)/(153)$
(238)	E_{FFL}	<u>FIELD VOLTS</u> at 100% load - This calculation is made with hot field resistance at expected temperature at 100% load.
		Field Volts = $(I_{FFL})(R_f \text{ hot}) = (237)(155)$
(241)	$I^2 R_{FL}$	<u>FIELD $I^2 R$</u> at 100% load - The copper loss in the field winding is calculated with hot field resistance at expected temperature for 100% load condition.
		Field $I^2 R = (I_{FFL})^2 (R_f \text{ hot}) = (237)^2 (155)$
(242)	W_{TFL}	<u>STATOR TEETH LOSS</u> at 100% load - The stator tooth loss under load increases over that of no load because of the parasitic fluxes caused by the ripple due to the rotor damper bar slot openings.
		$W_{TFL} = \left\{ 2 \left[.27 \left(\frac{X_d}{100} \right) \frac{(\% \text{ Load})}{100} \right]^{1.8} + 1 \right\} (W_{TNL})$ $= \left\{ 2 \left[.27 \left(\frac{133}{100} \right) 1 \right]^{1.8} + 1 \right\} (148)$

(243) W_{PFL} POLE FACE LOSS at 100% load

$$W_{PFL} = \left\{ \left[\frac{(K_{Sc})(I_{PH}) \frac{(\% \text{ Load})}{100} (n_s)}{(C)(F_g)} \right]^2 + 1 \right\} (W_{PNL})$$

$$= \left\{ \left[\frac{(242)(8) 1 (30)}{(32)(96)} \right]^2 + 1 \right\} (186)$$

(K_{Sc}) is obtained from Graph 3

(245) $I^2 R_L$ STATOR $I^2 R$ at 100% load - The copper loss based on the D.C. resistance of the winding. Calculate at the maximum expected operating temperature.

$$I^2 R = (m)(I_{PH})^2 (R_{SPH \text{ hot}}) \frac{(\% \text{ Load})}{100}$$

$$= (5)(8)^2 (54) 1$$

(246) -- EDDY LOSS - Stator $I^2 R$ loss due to skin effect

$$\text{Eddy Loss} = \left[\frac{(EF_{\text{top}}) + (EF_{\text{bot}})}{2} - 1 \right] (\text{Stator } I^2 R)$$

$$= \left[\frac{(55) - (56)}{2} - 1 \right] (245)$$

(247) -- TOTAL LOSSES at 100% load - sum of all losses at 100% load

$$\text{Total Losses} = (\text{Field } I^2 R) + (\text{F&W}) + (\text{Stator Teeth Loss})$$

$$+ (\text{Stator Core Loss}) + (\text{Pole Face Loss})$$

$$+ (\text{Stator } I^2 R) + (\text{Eddy Loss})$$

$$= (241) + (183) + (242) + (185) + (243) + (245) + (246)$$

(248) -- RATING IN KILOWATTS at 100% load

$$\text{Rating} = 3(E_{PH})(I_{PH}) \quad (\text{P.F.}) \frac{(\% \text{ Load})}{100} \times 10^{-3}$$

$$= 3(4)(8) \quad (9)(1.) \times 10^{-3}$$

(249) -- RATING AND LOSSES = (248) + (247) $\times 10^{-3}$

$$\begin{aligned} \text{(250)} \quad \text{--} \quad \% \text{ LOSSES} &= \left[\frac{\sum \text{LOSSES} \times 10^{-3}}{\text{Rating} + \text{Losses}} \right] 100 \\ &= \left[\frac{(247) \times 10^{-3}}{249} \right] 100 \end{aligned}$$

$$\begin{aligned} \text{(251)} \quad \text{--} \quad \% \text{ EFFICIENCY} &= 100\% - \% \text{ Losses} \\ &= 100\% - (250) \end{aligned}$$

These items can be recalculated for any load condition by simply inserting the values that correspond to the % load being calculated. The factor $\frac{(\% \text{ Load})}{100}$ takes care of (IPH) as it changes with load.

Note that values for F&W (183) and W_C (Stator Core Loss) (185) do not change with load, therefore, they can be calculated only once.

PASS 1

```

1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
2 FORMAT(F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0)
3 FORMAT(9X F12.5,2X F12.5)
7 READ2,VA,EE,EP,PN,F,PX,RPM,PI,PF,CK
    READ2,DL,DU,CL,HV,BV,SF,VL,BK,ZZ
    READ2,B0,B1,B2,B3,BS,HO,HX,HY,HZ,HS
    READ2,HT,HV,QQ,W,RF,SC,YY,C,DW,SN
    READ2,SN1,DW1,DB,CE,SH,SD,PRA,SK,T1,RS
    READ2,GC,C1,CW,CP,EL,CM,CQ,PE,BP1,BP2
    READ2,TP1,TP2,ALP,DR,WR,DL,TFP,DFP,DS1,ALSH
    READ2,P1,P2,P3,P4,P5,P7,DC1,ALCO,PT,FE
    READ2,RD,RT,T2,RR,SNL,WF
    SS=SF*(CL-HV*BV)                                EQ (17)
    HC=(DU-DL-2.0*HS)*0.5                           EQ (24)
    QN=QQ/(PX*PN)                                  EQ (25)
    TS=3.142*DL/QQ                                 EQ (26)
    IF(ZZ-4.0)9,10,9
9  TT=(0.667*HS+DL)*3.142/QQ                     EQ (27)
    GO TO 11
10 TT=((2.0*HO+BS)*0.66+DL)*3.1416/QQ
11 IF(ZZ-1.0)12,12,13
12 CC=(5.0*GC+BS)*TS/((5.0*GC+BS)*TS-BS*BS)   EQ (67)
    GO TO 14
13 QC=(4.44*GC+0.75*B0)*TS
    CC=QC/(QC-B0*B0)
14 CS=YY/(PN*QN)                                  EQ (31a)
    IF(CS-1.0)15,15,16
15 IF(CS-0.5)16,16,17

```

16 PR1=IT2,111.0

GO TO 7

17 TP=5.142*PI/PX

EQ (41)

IF(SK)18,18,19

18 FS=1.0

GO TO 20

19 FS=SIN(1.571*SK/TP)*TP/(1.571*SK)

EQ (42)

20 ZY=PX*P

IF(PBA-C0.)21,21,22

21 D=1.0

GO TO 25

22 D=2.0

23 U=0.0

24 U=U-1.0

D'=U*ZY

IF(QQ=D')26,25,24

25 DF=SIN(1.571*D/PW)/(QQ*D*SIN(1.571/(PW*QQ)))

EQ (43)

GO TO 27

26 DF=SIN(1.571*D/PW)/(QQ*D*SIN(1.571/(QQ*PW)))

EQ (44)

27 CF=SIN(YY*1.571/(PW*QN))

EQ (45)

EC=QQ*SC*CF*FS/C

GE=CC*SC

EQ (69)

IF(C1)29,28,29

28 C1=0.649*LOG(PE)+1.359

EQ (71)

29 IF(CM)30,30,31

30 CM=0.707*EE*C1*DF/(EP*PW)

EQ (72)

31 IF(CP)32,32,33

32 CP=PE*(LOG(GC/TP)*.0373+1.191)

EQ (73)

33 IF(EL)34,34,42

```

34 IF(RF)35,35,41
35 IF(PX-2.0)36,36,37
36 U=1.3
    GO TO 40
37 IF(PX-4.0)38,38,39
38 U=1.5
    GO TO 40
39 U=1.7
40 EL=3.142*U*YY*(DI+HS)/QQ+0.5          EQ (48)
    GO TO 42
41 EL=2.0*CE+3.142*(0.5*HX+DB)+YY*TS*TS/SQRT(TS*TS-BS*BS)
42 IF(CM)43,43,44
43 AA=SIN(3.142*PE)
    AB=SIN(1.571*PE)*4.0
    CM=(3.142*PE+AA)/AB                      EQ (74)
44 IF(CQ)45,45,46
45 AA=1.571*PE
    AB=3.1416*PE
    CQ=(0.5*COS(AA)+AB-SIN(AB))/(4.0*SIN(AA))
46 RB=(T1+234.5)*0.00394*RS                EQ (52)
    PRINT3,SS,CC,HC,GE,TS,C1,TT,CW,FS,CP,DF,EL,CF,CM,EC,CQ
    PUNCH1,VA,EE,EP,PN,F,PX
    PUNCH1,RPM,PI,PF,CK,POL,DI
    PUNCH1,PU,CL,SS,HC,SF,QN
    PUNCH1,WL,BK,ZZ,BO,B1,B2
    PUNCH1,B3,BS,HO,HX,HY,HZ
    PUNCH1,HS,HT,HW,QQ,W,RF
    PUNCH1,SC,YY,C,TS,SN,DB
    PUNCH1,CE,SH,SD,TT,SK,RB

```

PUNCH 1, ALCO,TP,D1,FE,RD,RT
PUNCH1,T2,RR,SNL,WF,PE,SN1
PUNCH1,DW1,BP1,BP2,TP1,TP2,ALP
PUNCH1,DR,WR,TFP,DFP,DS1,ALSH
PUNCH1,P1,P2,P3,P4,P5,P7
PUNCH 1,RS,GC,PT,C1,CW,CP
PUNCH 1,EL,CM,CQ,DW,CC,PBA
PUNCH 1,GE,CS,CF,FS,EC,DF
PUNCH 1,DC1
PAUSE
END

PASS 2

```
1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
DIMENSION DA(8),DX(6),DY(8),DZ(8)
READ 1,VA,EE,EP,PN,F,PX
READ 1,RPM,PI,PF,CK,POL,DI
READ 1,DU,CL,SS,HC,SF,QN
READ 1,VL,BK,ZZ,BO,B1,B2
READ 1,B3,BS,H0,HX,HY,HZ
READ 1,HS,HT,HV,QQ,W,RF
READ 1,SC,YY,C,TS,SN,DB
READ 1,CE,SH,SD,TT,SK,RB
READ 1,TP,D1,FE,RD,RT,COILS
READ 1,T2,RR,SNL,WF,PE,SN1
READ 1,DW1,BP1,BP2,TP1,TP2,ALP
READ 1,DR,WR,DY2,TY2,TY,ALY
READ 1,P1,P2,P3,P4,P5,P7
READ 1,G2,DG2,ALG2,AL1
READ 1,GE,CS,CF,FS,EC,DF
READ 1,RS,GC,PT,C1,CV,CP
READ 1,EL,CM,CQ,DW,CC,PBA
DT=DV1
IF(ZZ=3.0)49,50,51
49 SM=TT-BS
GO TO 53
50 SM=(3.1416*(DI+2.*HS)/QQ)-B3
GO TO 53
51 IF(ZZ=4.0)50,52,49
52 SM=TT-BS*(0.554-0.888*H0/BS)
53 HM=CL+EL
```

IF(DT) 61,61,62

61 AC=0.785*DW*DW*SN1

GO TO 72

62 ZY=0.0

DA(1)=0.05

DA(2)=0.072

DA(3)=0.125

DA(4)=0.165

DA(5)=0.225

DA(6)=0.438

DA(7)=0.688

DA(8)=1.5

DX(1)=0.000124

DX(2)=0.00021

DX(3)=0.00021

DX(4)=0.00084

DX(5)=0.00189

DX(6)=0.00189

DY(1)=0.000124

DY(2)=0.000124

DY(3)=0.00084

DY(4)=0.00084

DY(5)=0.00189

DY(6)=0.00335

DY(7)=0.00754

DY(8)=0.03020

DZ(1)=0.000124

DZ(2)=0.000124

DZ(3)=0.000124

DZ(4)=0.00335
DZ(5)=0.00335
DZ(6)=0.00754
DZ(7)=0.0134
DZ(8)=0.0302

63 IF(DT-.05)201,200,200
200 JA=0
JB=0
JC=0
JD=0

64 JA=JA+1
JB=JB+1
JC=JC+1
JD=JD+1
IF(DT-DA(JA))65,65,64

201 D=0
IF(ZY)71,71,54

65 IF(DW-0.188)66,66,67

66 CY=DX(JB-1)
CZ=DX(JB)
GO TO 70

67 IF(DW-0.75)68,68,69

68 CY=DY(JC-1)
CZ=DY(JC)
GO TO 70

69 CY=DZ(JD-1)
CZ=DZ(JD)

70 D=CY+(CZ-CY)*(DT-DA(JA-1))/(DA(JA)-DA(JA-1))
IF(ZY)71,71,54

71 AC=(DT*DV-D)*SN1
 72 IF(RT)73,73,74
 73 AS=0.785*RD*RD
 GO TO 55
 74 ZY=1.0
 DT=RT
 DV=RD
 GO TO 63
 54 AS=RT*RD-D
 55 S=PI/(C*AC)
 CY=PI *FE*0.000001/AS
 FK=RF*CY
 FP=(T2+234.5)*FK*0.00394
 RC=0.321*PT *FE*AS
 IF(SH)202,203,202
 203 ET=1
 EB=1
 GO TO 204
 202 AA=0.584+(SN*SN-1.0)*0.0625*(SD*CL/(SH*HM))**2.0
 AB=(SH*SC*F*AC/(BS*RB))**2.0
 ET=AA*AB*0.00135+1.0
 EB=ET-0.00168*AB
 204 RY=SC*001*0.000001*HM/(PN*AC*C*C)
 RG=RS*RY
 RP=RB*PY
 A=PI*SC*CF/(C*TS)
 PUNCH1,VA,EE,EP,PN,F,PX
 PUNCH1,RPM,PI,PF,CK,POL,DI
 PUNCH1,DU,CL,SS,HC,SF,ON

PUNCH1,WL,BK,ZZ,BO,B1,B2
PUNCH1,B3,BS,H0,HX,HY,HZ
PUNCH1,HS,HT,HW,QQ,W,RF
PUNCH1,SC,YY,C,TS,SN,DB
PUNCH1,CE,SH,SD,TT,SK,RB
PUNCH1,RS,GC,GP,C1,CW,CP
PUNCH1,EL,CM,CQ,DW,CC,PBA
PUNCH1,G4,CS,CF,FS,EC,DF
PUNCH1,G,GE,RS,TP,BNE,BSE
PUNCH1,BNM,BSM,PNL,PSL,DR,HNP
PUNCH1,D1,W0,HD,DD,H,B
PUNCH1,BN,SB,TB,RE,T3,PT
PUNCH1,FE,RD,RT,T2,RR,SNL
PUNCH1,WF,HM,SM,AC,AS,ET
PUNCH1,EB,S,FK,FR,RC,RG
PUNCH1,RP,A,PE,DDR,AD
PAUSE
END

PASS 3

```

1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)

READ1 ,VA,EE,EP,PN,F,PX
READ1 ,RPM,PI,PF,CK,POL,DI
READ1 , DU,CL,SS,HC,SF,QN
READ1 , WL,BK,ZZ,BO,B1,B2
READ1 , B3,BS,HO,HX,HY,HZ
READ1 ,HS,HT,HW,QQ,W,RF
READ1 ,SC,YY,C,TS,SN,DB
READ1 ,CE,SH,SD,TT,SK,RB
READ1 ,RS,GC,GP,C1,CW,CP
READ1 ,EL,CM,CQ,DW,CC,PBA
READ1 ,G4,CS,CF,FS,EC,DF
READ1 ,G,GE,RS,TP,BNE,BSE
READ1 ,BNM,BSM,PNL,PSL,DR,HNP
READ1 ,D1,W0,HD,DD,H,B
READ1 ,BN,SB,TB,RE,T3,PT
READ1 ,FE,RD,RT,T2,RR,SNL
READ1 ,WF,HM,SM,AC,AS,ET
READ1 ,EB,S,FK,FR,RC,RG
READ1 ,RP,A,PE,DDR,AD
    IF(PBA-60.0)105,105,108
105 IF(CS-0.667)106,106,107
106 FF=0.25*(6.0*CS-1.0)
107 FF=0.25*(3.*CS+1.0)                                EQ (61)
GO TO 75
108 IF(CF-0.667)109,109,110
109 FF=0.05*(24.0*CS-1.0)
GO TO 75

```

110 FF=0.75

75 CX=FF/(CF*CF*DF*DF) EQ (60)

Z=CX*20.0/(PN*QN)

BT=3.142*D1/00-B0

ZA=BT*BT/(16.0*TS*GC)

ZB=0.35*BT/TS

ZC=H0/B0

ZD=HX*0.333/BS

ZE=HY/BS

IF(ZZ-2.0) 76,77,78

76 PC=Z*(ZE+ZD+ZA+ZB) EQ (62)

GO TO 82

77 PC=Z*(ZC+(2.0*HT/(B0+BS))+(HW/BS)+ZD+ZA+ZB)

GO TO 82

78 IF(ZZ-4.0) 79,80,81

79 PC=Z*(ZC+(2.0*HT/(B0+B1))+(2.0*HW/(B1+B2))+(HX*0.333/B2)+ZA+ZB)

GO TO 82

80 PC=Z*(ZC+0.62)

GO TO 82

81 PC=Z*(ZE+ZD+(0.5*GC/TS)+(0.25*TS/GC)+0.6)

82 EK=EL/(10.0***(0.103*YY*TS+0.402))

IF(D1-8.0) 83,83,84

83 EK=SQRT(EK) EQ (63)

84 ZF=.612*LOG(10.0*CS)

EW=6.28*EK*ZF*(TP***(0.62-(0.228*LOG(ZF))))/(CL*DF*DF)

87 ZA=3.1416*(D1+HS)/QQ

IF(ZZ-3.0) 88,89,88

88 TM=ZA-BS EQ (57)

GO TO 90

89 TM=(3.1416*(D1+2.*HS)/QQ)-B3
90 WI=(TM*QQ*SS*HS+(DU-HC)*3.142*HC*SS)*0.283
IF(WF)445,446,445
446 WF=2.52E-6*(DR**2.5)*ALP*RPM**1.5
445 WC=.321*HM*QQ*AC*SC
PUNCH1,VA,EE,EP,PN,F,PX
PUNCH1,RPM,PI,PF,CK,POL,DI
PUNCH1,DU,CL,SS,HC,SF,QN
PUNCH1,WL,BK,ZZ,B0,B1,B2
PUNCH1,B3,BS,HO,HX,HY,HZ
PUNCH1,HS,HT,HW,QQ,W,RF
PUNCH1,SC,YY,C,TS,SN,DB
PUNCH1,CE,SH,SD,TT,SK,RB
PUNCH 1, ALCO,TP,D1,FE,RD,RT
PUNCH1,T2,RR,SNL,WF,PE,SN1
PUNCH1,DW1,BP1,BP2,TP1,TP2,ALP
PUNCH1,DR,WR,TFP,DFP,DS1,ALSH
PUNCH1,P1,P2,P3,P4,P5,P7
PUNCH 1,RS,GC,PT,C1,CW,CP
PUNCH 1,EL,CH,CQ,DW,CC,PBA
PUNCH 1,GE,CS,CF,FS,EC,DF
PUNCH1,HM,SM,AS,AC,ET,EB
PUNCH1,S,FK,FR,RC,RG,RP
PUNCH1,FF,CX,PC,EK,EW,TM
PUNCH1,A,DC1,WI,WC
PAUSE
END

PASS 4

```

3 FORMAT(9X F12.5,2X F12.5)
1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)

READ1 ,VA,EE,EP,PN,F,PX
READ1 ,RPM,P1,PF,CK,POL,DI
READ1 ,DU,CL,SS,HC,SF,QN
READ1 ,WL,BK,ZZ,B0,B1,B2
READ1 ,B3,BS,HO,HX,HY,HZ
READ1 ,HS,HT,HW,OO,W,RF
READ1 ,SC,YY,C,TS,SN,DB
READ1 ,CE,SH,SD,TT,SK,RB
READ1 , ALCO,TP,D1,FE,RD,RT
READ1 ,T2,RR,SNL,WF,PE,SN1
READ1 ,DW1,BP1,BP2,TP1,TP2,ALP
READ1 ,DR,WR,TFP,DFP,DS1,ALSH
READ1 ,P1,P2,P3,P4,P5,P7
READ1 ,RS,GC,PT,C1,CW,CP
READ1 ,EL,CM,CQ,DW,CC,PBA
READ1 ,GE,CS,CF,FS,EC,DF
READ1 ,HM,SM,AS,AC,ET,EB
READ1 ,S,FK,FR,RC,RG,RP
READ1 ,FF,CX,PC,EK,EW,TM
READ1 ,A,DC1,W1,WC
AP=BP2*TP2
IF(P1)400,401,400
401 R2=(DR-DFP)/2.
R1=R2-TP1
P1=2.*BP1*LOG(R2/R1)
400 IF(P2)402,403,402

```

EQ (77b)

EQ (80)

403 AL2=TP-(BP1+BP2)/2.
 $P2=3.19*ALP*((TP2+TP1)/2.)/AL2$ EQ (81)

402 IF(P3)404,405,404

405 R3=ALCO-ALP/2.
 $R4=ALCO-ALP$
 $P3=(6.38*((3.*BP1+BP2)/4.)/3.1416)*LOG(R3/R4)$ EQ (82)

404 IF(P4)406,407,406

407 IF(PX-4.)408,408,409

409 P4=(3.19*ALP/3.1416)*LOG(1.+(BP1+BP2)/AL2) EQ (83)

GO TO 406

408 P4=(4.785*ALP/3.1416)*LOG(1.+(BP1+BP2)/AL2)

406 IF(P5)410,411,410

411 P5=(6.675/ALCO)*(DC1**2/4.-DS1**2/4.) EQ (84)

410 IF(P7)412,413,412

413 AL7=(DU-DR)/2.
 $P7=(5.011*((DR+DU)/2.)*((DU-DR)/2.)+3.1416*DR*TFP)/AL7$ EQ (86)

412 TG=6.E6*EE/(CW*EC*RPH)
 $BT1=TG/(QQ*SS*SM)$ EQ (91)

$FQ=TG*CP/PX$ EQ (92)

$BC1=FQ/(2.*HC*SS)$ EQ (94)

$BG1=TG/(3.1416*D1*CL)$ EQ (95)

$FG=BG1*GE/.00319$ EQ (96)

$ALA=6.38*D1/(PX*GE)$

$PGE=PX*(P1+P2+P3+P4)+P5$ EQ (160a)

$ALF=PGE/CL$ EQ (160)

$XR=.0707*A*DF/(BG1*C1)$ EQ (129)

$XL=XR*(PC+EW)$ EQ (130)

$XD=XR*C1*CH*ALA$ EQ (131)

$XQ=XR*CQ*ALA$ EQ (132)

XA=XL+XD EQ (133)
 XB=XL+XQ EQ (134)
 VR=3.1416*DR*RPM/12. EQ (145)
 XF=XD*((1.-(C1/CH)/(2.*CP+(4.*ALF/(3.1416*ALA))))) EQ (160)
 SI=PT*PT*ALP*(CP*ALA*1.57+ALF)*1.E-8 EQ (161)
 XU=XL+XF EQ (166)
 XS=.88*XU EQ (167)
 XX=XS EQ (168)
 XY=XB EQ (169)
 XN=.5*(XX+XY) EQ (170)
 IF(W) 414, 415, 414
 415 X0=0.
 GO TO 422
 414 IF(CS-1.) 417, 418, 417
 418 AKX=1.
 AKX1=1.
 GO TO 419
 417 AA=(3.*YY/(PN*QN))
 AKX=AA-2.
 IF(AA/3.-.667) 420, 420, 421
 420 AKX1=.75*AA-.25
 GO TO 419
 421 AKX1=.75*AA+.25
 419 ABL=(AKX/(CF**2))*07*ALA
 X0=AKX*(ABL+PC)/AKX1
 X0=XR*(X0+(1.667*(HX+3.*HZ))/(PN*QN*CF**2*DF**2*BS)+.2*EW) EQ (172)
 422 TC=SI/FK EQ (176)
 RA=PN*PI*PI*RG/(VA*1000.)
 TA=XN/(628.32*F*RA) EQ (177)

T5=X\$TC/XA EQ (178)
IF(F=60.) 425,426,425
425 T4=.005 EQ (178)
GO TO 427
426 T4=.035
427 FSC=XAFG EQ (180)
PRINT3,AC,A,S,XR,H#,XL,RG,XD,RP,XQ,ET,XA,EB,XB,PC,XF,EW,SI,WC,XU
PRINT3,WI,XS,TP,XH,WR,XO,VR,TC,AS,TA,FK,T5,FR,T4,RC,TG,P1,FQ
PRINT3,P2,BG1,P3,BT1,P4,BC1
PUNCH1, BK, WL, QO, SH, BS, RP, P1
PUNCH1, TS, BO, GC, C1, D1, CL
PUNCH1, ET, EB, C, SC, PH, P1
PUNCH1, HS, BT1, BC1, DU, HC, PX
PUNCH1, PGE, F0, AP, ALP, P7, FG
PUNCH1, DS1, ALSH, PT, FR, AS, PF
PUNCH1, XB, XA, CK, XD, PUL, SNL
PUNCH1, FK, RP, RG, EP, BG1, SS
PUNCH1, D1, FSC, P5, WF, EP, EE
PAUSE
END

PASS 5

```

1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
DIMENSION GB(4),AE(4),DX(4)
READ1 , BK,WL,QQ,SM,BS,RPM
READ1, TS,BO,GC,C1,D1,CL
READ1 ,ET,EB,C,SC,PN,PI
READ1 ,HS,BT1,BC1,DU,HC,PX
READ1 ,PGE,FQ,AP,ALP,P7,FG
READ1 ,DS1,ALSH,PT,FR,AS,PF
READ1 ,XB,XA,CK,XD,POL,SNL
READ1 ,FK,RP,RG,EP,BG1,SS
READ1 ,D1,FSC,P5,WF,EP,EE
WQ=(DU-HC)*1.42*HC*SS*(BC1/BK)**2.0*WL          EQ (185)
WT= SM      *QQ*SS*HS*0.453*(BT1/BK)**2.0*WL      EQ (184)
132 D2=BG1**2.5*0.000061
D3=(0.0167*QQ*RPM)**1.65*0.000015147
IF(TS-0.9)133,133,134
133 D4=TS**1.285*0.81
GO TO 137
134 IF(TS-2.0)135,135,136
135 D4=TS**1.145*0.79
GO TO 137
136 D4=TS**0.79*0.92
137 D7=BO/GC
IF(D7-1.7)138,138,139
138 D5=D7**2.31*0.3
GO TO 144
139 IF(D7-3.0)140,140,141
140 D5=D7**2.0*0.35

```

GO TO 144

141 IF(D7=5.0) 142, 142, 143

142 D5=D7*1.4*0.625

GO TO 144

143 D5=D7*0.965*1.33

144 D6=10.0**((0.932*C1-1.606)

BA=3.142*D1*CL

W1=0.1*D2*D3*D4*D5*D6*BA

EQ (186)

AXX=BU/GC

IF(AXX-1.) 964, 965, 964

965 AKSC=2.6

GO TO 957

964 IF(AXX-3.75) 955, 955, 956

955 AKSC=10.**.178/((AXX-1.)*.334)

GO TO 957

956 AKSC=10.**.11/((AXX-1.)*.174)

957 XX1=P1*P1*P1

XX3=3.*EP*P1*PF

XX2=(ET+EB)/2.-1.

XX4=AKSC*P1*SC/(C*FG)

GB(1)=1.

GB(2)=1.5

GB(3)=2.

GB(4)=POL

AN=ATAN(SORT(1.-PF*PF)/PF)

EQ (198)

AN1=SIN(AN)

DO 777 K=1,4

YB=GB(K)

AA =ATAN((AN1+XB*YB/100.)/PF)

AE(K)=COS(AA-AN)+XA*SIN(AA)*YB/100.

EQ (198)

777 DX(K)=.93*XD*YB*SIN(AA)/100.

EQ (213)

PUNCH1,AE(1),AE(2),AE(3),AE(4)

PUNCH1,DX(1),DX(2),DX(3),DX(4)

PUNCH1,HS,BT1,BC1,DU,HC,PX

PUNCH1,PGE,FQ,AP,ALP,P7,FG

PUNCH1,DS1,ALSH,PT,FR,AS,PF

PUNCH1,XB,XA,CK,XD,POL,SNL

PUNCH1,WQ,WN,WF,XX1,XX2,XX3

PUNCH1,FK,RP,RG,XX4,FSC,P5

PUNCH1,WT,EE

PAUSE

END

20

PASS 6

DIMENSIONBSHL(4),BPL(4),FFL(4),CDD(4),AIFL(4),EPFL(4)

DIMENSION AE(4),DX(4),AI(90),PTL(4),PLL(4)

700 FORMAT (13)

3 FORMAT(9X F12.5,2X F12.5)

4 FORMAT (9X F12.5/)

1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)

888 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)

K=1

823 READ888,AI(K),AI(K+1),AI(K+2),AI(K+3),AI(K+4),AI(K+5)

K=K+6

IF (K-89)823,824,824

824 READ1,AE(1),AE(2),AE(3),AE(4)

READ1,DX(1),DX(2),DX(3),DX(4)

READ1 ,HS,BT1,BC1,DU,HC,PX

READ1 ,PGE,FQ,AP,ALP,P7,FG

READ1 ,DS1,ALSH,PT,FR,AS,PF

READ1 ,XB,XA,CK,XD,POL,SNL

READ1 ,WQ,WN,WF,XX1,XX2,XX3

READ1 ,FK,RP,RG,XX4,FSC,P5

READ1 ,WT,EE

ASH=.7854*DS1*DS1

EQ (113)

COREL=(.7854*(DU-HC)/PX)

EQ (98)

LOAD=1

X=BT1

NA=1

K=1

GO TO 802

806 FT=HS*AT

EQ (97)

X=BC1
 K=2
 NA=1
 GO TO 802

807 FC=COREL*AT EQ (98)
 FS=FT+FC EQ (98a)
 PL=PGE*(FG+FS)*.001 EQ (100)
 PLT=FQ+PL EQ (102)
 BP=PLT/AP EQ (103)
 X=BP
 NA=31
 K=3
 GO TO 802

808 FP=AT*ALP EQ (104)
 PL7=P7*(FP+FG+FS)*.001 EQ (99)
 PSH=(PLT*PX/2.0)+PL7 EQ (111)
 BSH=PSH/ASH EQ (113)
 X=BSH
 NA=61
 K=4
 GO TO 802

809 FSH=ALSH*AT EQ (114)
 FNL=2.*(FG+FS+FP)+FSH EQ (127)
 AINL=FNL/PT EQ (127a)
 EPNL=AINL*FK EQ (127b)
 CD=AINL/AS EQ (127c)
 SCR=FNL/FSC EQ (181)
 PRINT3,P5,FT,P7,FC,FSC,FG
 PRINT4,SCR

LOAD=2
 DO 899 J=1,4
 AED=AE(J) EQ (198)
 $PLL(J)=PL*((AED*FG+(1.+PF)*FT+FC)/(FG+FS))$ EQ (196a)
 IF (PF-.95)825,825,826
 825 PPL=FQ*(AED-DX(J)) EQ (213)
 GO TO 827
 826 PPL=FQ*CK
 827 PTL(J)=PPL+PLL(J) EQ (213a)
 PPTL=PTL(J)
 $X=PPTL/AP$ EQ (213b)
 $BPL(J)=X$
 $NA=31$
 $K=1$
 GO TO 802
 841 FPL=AT*ALP EQ (213c)
 $AA=(AED*FG+FPL+FT*(1.+PF)+FC)$
 $PL7L=.001*P7*AA$ EQ (207)
 $PSHL=PPTL*PX/2.+PL7L$ EQ (231a)
 $X=PSHL/ASH$ EQ (232)
 $BSHL(J)=X$
 $NA=61$
 $K=2$
 GO TO 802
 842 FSHL=ALSH*AT EQ (233)
 $FFL(J)=AA*2.+FSHL$ EQ (236)
 $AIFL(J)=FFL(J)/PT$ EQ (237)
 $CDD(J)=AIFL(J)/AS$ EQ (239)
 899 EPFL(J)=AIFL(J)*FR EQ (238)

837 JA=JA/2
PUNCH700,JA
IF(JA)891,892,891
891 DU 890 K=1,JA
PUNCH1,BPL(K),BSHL(K),FFL(K),AIFL(K),CDD(K),EPFL(K)
890 PUNCH1,PTL(K),PLL(K)
892 PUNCH1,XX1,XX2,XX3,XX4,WT,WQ
PUNCH1,WF,WN,RP,RG,FK,FR
PUNCH1,BP,BSH,FNL,A1NL,CD,EPNL
PUNCH1,SNL,FP,BT1,FQ,BC1
PUNCH1,FG,AT,HS,COREL,P7,PGE
PUNCH1,AP,ALP,PX,ALSH,ASH
PUNCH 1,PL,PLT,POL,XA,EE
PAUSE
802 IF(AI(NA)-X)830,831,831
831 NA=NA+3
835 IF(AI(NA)-X)833,834,834
833 NA=NA+2
GO TO 835
834 AX=AI(NA)
BB1=AI(NA-2)
DC=AI(NA+1)
D=AI(NA-1)
XX= (AX-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
Y=AX-XX*.4343*LOG(DC)
AT=EXP(2.306*(X-Y)/XX)
GO TO (838,839),LOAD
838 GO TO (806,807,808,809,810),K
839 JA=JA+1

GO TO (841,842),K
830 GO TO (836,837),LOAD
836 PRINT 850,
850 FORMAT (17H) MACHINE SATURATED)
PAUSE
END

PASS 7

```
DIMENSION BPL(4),BSHL(4),FFL(4),AIFL(4),CDD(4),EPFL(4),FCUL(4)
DIMENSION WNL(4),STTL(4),SCUL(4),EDDL(4),TOTL(4),PEFF(4),GB(4)
DIMENSION PLL(4),PTL(4)
961 FORMAT(F11.3,8X F11.3,F11.3,F11.3,F11.3)
700 FORMAT (13)
1 FORMAT (E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
DO 705 N=1,4
  PLL(N)=0
  PTL(N)=0
  BPL(N)=0
  BSHL(N)=0
  FFL(N)=0
  AIFL(N)=0
  CDD(N)=0
  EPFL(N)=0
  FCUL(N)=0
  WNL(N)=0
  STTL(N)=0
  SCUL(N)=0
  EDDL(N)=0
  TOTL(N)=0
705 PEFF(N)=0
READ700,JA
  IF(JA)702,703,702
702 DO 704 K=1,JA
  READ1,BPL(K),BSHL(K),FFL(K),AIFL(K),CDD(K),EPFL(K)
704 READ1 ,PTL(K),PLL(K)
703 READ1 ,XX1,XX2,XX3,XX4,WT,WQ
```

READ1 ,MF,VN,RP,RG,FK,FR
 READ1 ,BP,BSH,FNL,A1NL,CD,EPNL
 READ1,SNL,FP,BT1,FQ,BC1
 READ1,FG,AT,HS,COREL,P7,PGE
 READ1 ,AP,ALP,PX,ALSH,ASH
 READ 1,PL,PLT,POL,XA,EE
 IF(SNL)707,706,707
 707 PUNCH1,SNL,BT1,FQ,BC1,EE
 PUNCH1,FG,HS,COREL,P7,PGE
 PUNCH1,AP,ALP,PX,ALSH,ASH
 706 FEL=A1NL+A1NL*FK
 TL=FEL+VT+WQ+VN +WF
 ABX=0
 IF(JA)714,712,714
 714 IF(JA-1) 708,709,708
 709 IF(POL)708,710,708
 710 JA=JA-1
 708 GB(1)=1.
 GB(2)=1.5
 GB(3)=2.
 GB(4)=POL
 DO 711 K=1,JA
 YB=GB(K)
 FCUL(K)=A1FL(K)**2*FR
 STTL(K)=((.0027*XA*YB)**2*2.+1.)*VT
 WNL(K)=((XX4*YB)**2+1.)*VN
 SCUL(K)=XX1*RP*YB
 EDDL(K)=SCUL(K)*XX2
 TOTL(K)=EDDL(K)+SCUL(K)+WNL(K)+STTL(K)+FCUL(K)+WQ+WF

EQ (182)

EQ (196)

EQ (241)

EQ (242)

EQ (243)

EQ (245)

EQ (246)

EQ (247)

711 PEFF(K)=XX3*YB*100./(XX3*YB+TOTL(K)) EQ (251)

712 IF(POL)958,959,958

958 PRINT961,PL,PLL(1),PLL(2),PLL(3),PLL(4)

PRINT961,BP,BPL(1),BPL(2),BPL(3),BPL(4)

PRINT961,PLT,PTL(1),PTL(2),PTL(3),PTL(4)

PRINT961,BSH,BSHL(1),BSHL(2),BSHL(3),BSHL(4)

PRINT961,FNL,FFL(1),FFL(2),FFL(3),FFL(4)

PRINT961,AINL,AIFL(1),AIFL(2),AIFL(3),AIFL(4)

PRINT961,CD,CDD(1),CDD(2),CDD(3),CDD(4)

PRINT961,EPNL,EPFL(1),EPFL(2),EPFL(3),EPFL(4)

PRINT961,WQ,WQ,WQ,WQ,WQ

PRINT961,WT,STTL(1),STTL(2),STTL(3),STTL(4)

PRINT961,ABX,SCUL(1),SCUL(2),SCUL(3),SCUL(4)

PRINT961,ABX,EDDL(1),EDDL(2),EDDL(3),EDDL(4)

PRINT961,VN,VNL(1),VNL(2),VNL(3),VNL(4)

PRINT961,FEL,FCUL(1),FCUL(2),FCUL(3),FCUL(4)

PRINT961,WF,WF,WF,WF,WF

PRINT961,TL,TOTL(1),TOTL(2),TOTL(3),TOTL(4)

PRINT961,ABX,PEFF(1),PEFF(2),PEFF(3),PEFF(4)

PAUSE

959 PRINT961,PL,PLL(1),PLL(2),PLL(3)

PRINT961,PLT,PTL(1),PTL(2),PTL(3)

PRINT961,BP,BPL(1),BPL(2),BPL(3)

PRINT961,BSH,BSHL(1),BSHL(2),BSHL(3)

PRINT961,FNL,FFL(1),FFL(2),FFL(3)

PRINT961,AINL,AIFL(1),AIFL(2),AIFL(3)

PRINT961,CD,CDD(1),CDD(2),CDD(3)

PRINT961,EPNL,EPFL(1),EPFL(2),EPFL(3)

PRINT961,WQ,WQ,WQ,WQ,WQ

```
PRINT961,WT,STTL(1),STTL(2),STTL(3)
PRINT961,ABX,SCUL(1),SCUL(2),SCUL(3)
PRINT961,ABX,EDDL(1),EDDL(2),EDDL(3)
PRINT961,VN,VNL(1),VNL(2),VNL(3)
PRINT961,FEL,FCUL(1),FCUL(2),FCUL(3)
PRINT961,WF,WF,WF,WF
PRINT961,TL,TOTL(1),TOTL(2),TOTL(3)
PRINT961,ABX,PEFF(1),PEFF(2),PEFF(3)
PAUSE
END
```

PASS 6

DIMENSION A1(90)

```
1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
800 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)
870 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5)
879 FORMAT(F12.5,F12.5,F12.5,F12.5,F12.5,F12.5//)
```

K=1

823 READ 800,A1(K),A1(K+1),A1(K+2),A1(K+3),A1(K+4),A1(K+5)

K=K+6

IF (K=89) 823, 824, 824

824 READ 1,SHL,BT1,FQ,BC1,EE

READ 1,FG,HS,COREL,P7,PGE

READ 1,AP,ALP,PX,ALSH,ASH

YB = 0

LOAD=1

DO 800 N=1,9

R1=BT1*YB

R2=FQ*YB

R3=BC1*YB

R4=FG*YB

R5=EE*YB

X=R1

NA=1

K=1

GO TO 802

806 FT=HS*AT

EQ (97)

X=R3

K=2

NA=1

GO TO 802

807 FC=COREL^{AT} EQ (98)
 FS=FT+FC EQ (98a)
 PL=PGE*(R4+FS)*.001 EQ (100)
 PLT=R2+PL EQ (102)
 BP=PLT/AP EQ (103)
 X=BP
 NA=31
 K=3
 GO TO 802

808 FP=AT*ALP EQ (104)
 PL7=P7*.001*(FP+FS+R4) EQ (99)
 PSH=(PL7*PX/2.0)+PL7 EQ (111)
 BSH=PSH/ASH EQ (113)
 X=BSH
 NA=61
 K=4
 GO TO 802

809 FSH=ALSH*AT EQ (114)
 FNL=2.0*(R4+FS+FP)+FSH EQ (127)
 PRINT878,R5,R1,FT,R3,FC,R4
 PRINT879,PL,PLT,BP,FP,BSH,FNL

800 YB=YB+.1
 PAUSE

802 IF(AI(NA)-X)830,831,831

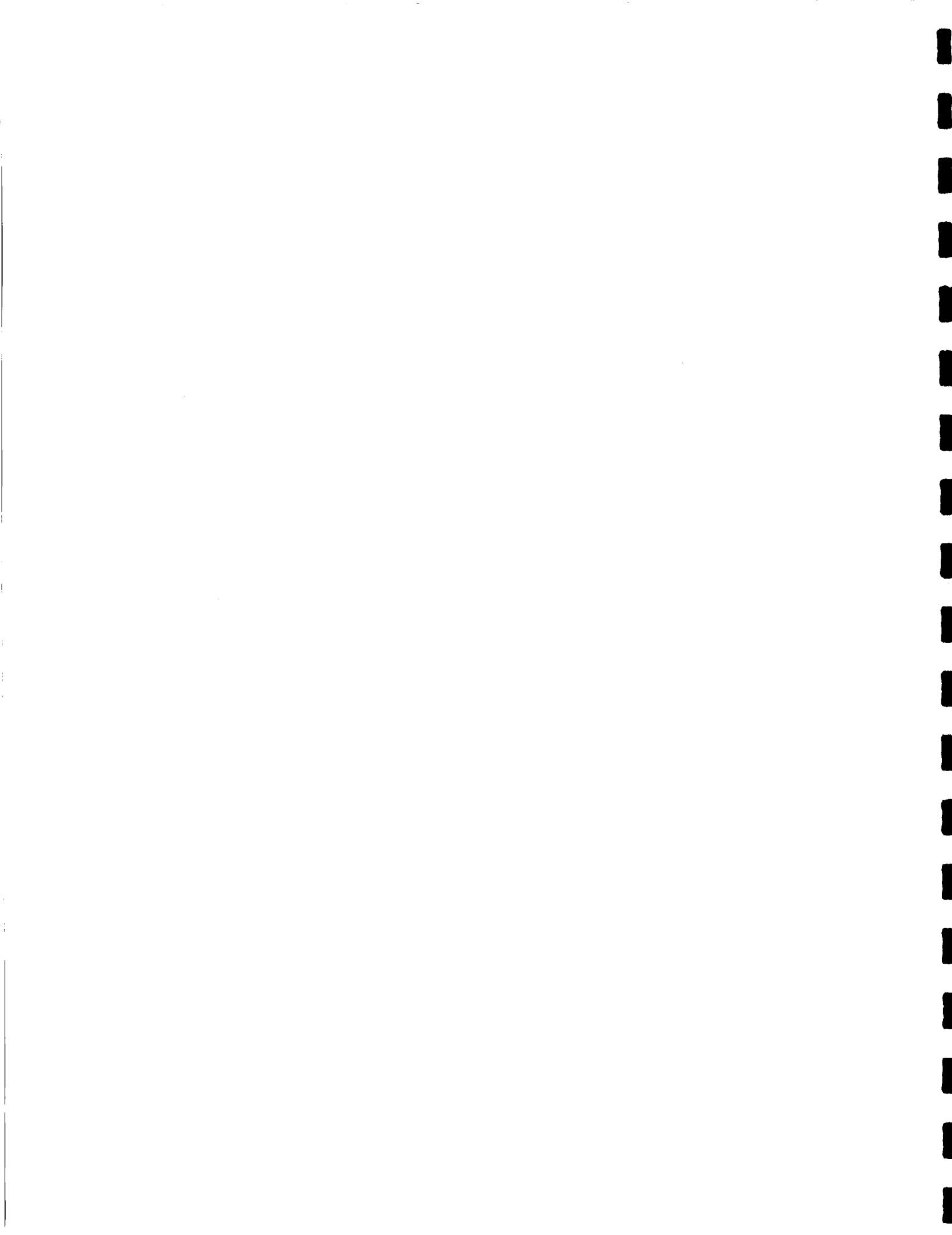
831 NA=NA+3

835 IF(AI(NA)-X)833,834,834

833 NA=NA+2

GO TO 835

834 AX=A1(NA)
BB1=A1(NA-2)
DC=A1(NA+1)
D=A1(NA-1)
XX= (AX-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
Y=AX-XX*.4343*LOG(DC)
AT=EXP(2.306*(X-Y)/XX)
GO TO (838,839),LOAD
838 GO TO (806,807,808,809,810),K
839 JA=JA+1
GO TO (841,842),K
830 GO TO (836,837),LOAD
836 PRINT 850,
850 FORMAT (17Hmachine saturated)
PAUSE
END



SUPPLEMENT TO DESIGN MANUAL
FOR PERMEANCE CALCULATIONS

Permeance (P) is the property of a magnetic circuit, or any part of a circuit, which determines the total flux corresponding to a given mmf as indicated in the expression -

$$\emptyset = F P = \text{mmf} \times \text{permeance}$$

From "Standard Handbook for Electrical Engineers" A. E. Knowlton,
7th edition, McGraw-Hill, Section 4-310.

Magnetic Permeability (μ) is that property of an isotropic medium which determines under specified conditions, the magnitude relation between magnetic induction and magnetizing force in the medium usually expressed -

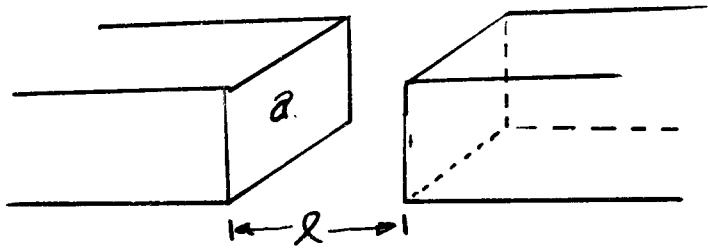
$$\mu = \frac{B}{H}$$

Same reference Section 4-308.

For air $\mu = 3.19$
$$\frac{\text{Flux Line/inch}^2}{\text{Ampere Turns/inch}}$$

The following formulas are from Roter's "Electromagnetic Devices"

Parallel planes of infinite extent

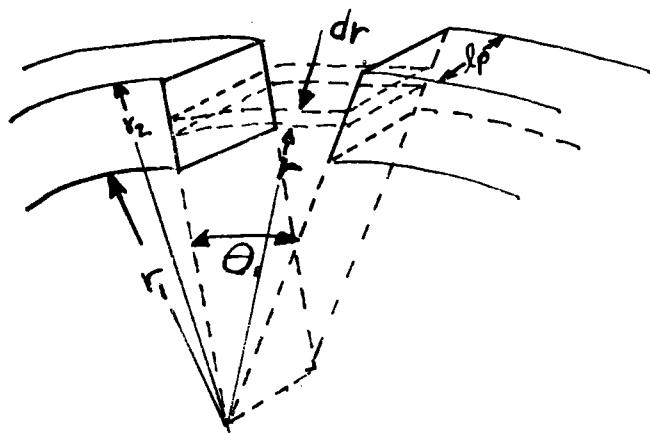


$$P = u \frac{a}{l}$$

where a = area

l = length of flux path

NON-PARALLEL PLANES OF INFINITE EXTENT



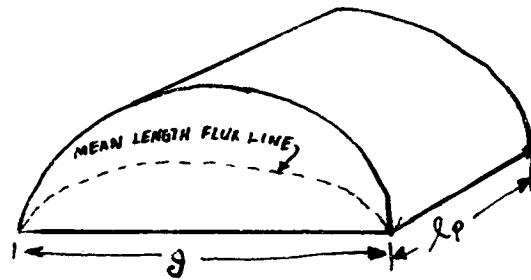
$$dP = \frac{u l_p dr}{\theta r}$$

$$P = \frac{u l_p}{\theta} \int_{r_1}^{r_2} \frac{dr}{r}$$

$$P = \frac{u l_p}{\theta} \ln \frac{r_2}{r_1}$$

Special formulas for use in estimating permeances of flux paths.

SEMI-CIRCULAR CYLINDRICAL VOLUME



Mean length of flux line has been found by graphical measurement to be

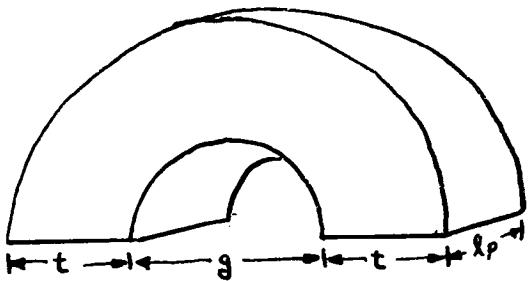
1.22 g.

Mean area of flux path found by dividing the entire volume by mean length of flux path is,

$$\text{Mean area} = \frac{\pi g^2 l_p}{8} \times \frac{1}{1.22 \text{ g}} = 0.322 \text{ g } l_p$$

$$P = \frac{u a}{l} = \frac{0.322 u \text{ g } l_p}{1.22 \text{ g}} = 0.26 u l_p$$

HALF ANNULUS



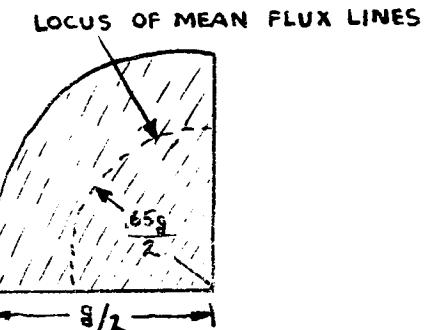
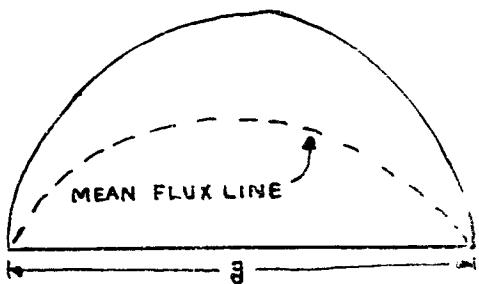
NOTE: IN THE COMPUTER DESIGN MANUAL THE SYMBOL g WAS CHANGED
TO z TO AVOID CONFUSION WITH g (AIR GAP)

Assume the mean length of the flux path to be $\pi(\frac{g+t}{2})$ and the average area of the path to be $t l_p$ then

$$P = \frac{ua}{l} = \frac{2utl_p}{\pi(g+t)} = 0.64 \frac{ul_p}{\left(\frac{g}{t} + 1\right)}$$

WHEN $g < 3t$ $P = \frac{ul_p}{\pi} \ln \left(1 + \frac{2t}{g}\right)$

SPHERICAL QUADRANT



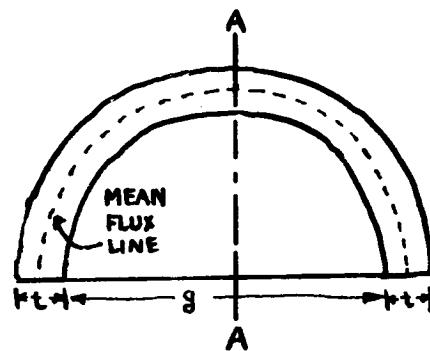
By graphical measurement, the mean flux line is 1.3 g. Volume of quadrant is $\frac{1}{3}\pi\left(\frac{g}{2}\right)^3$, hence mean area of flux path is -

$$\frac{\frac{1}{3}\pi\left(\frac{g}{2}\right)^3}{1.3 \text{ g}} = 0.1 \text{ g}^2$$

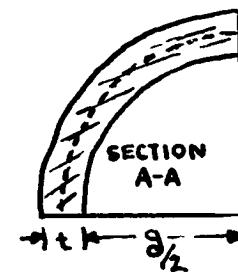
and the permeance is

$$P = \frac{uA}{\lambda} = \frac{0.1 \text{ g}^2 u}{1.3 \text{ g}} = 0.077 \text{ ug}$$

QUADRANT OF SPHERICAL SHELL



LOCUS OF MEAN FLUX LINES



Mean length of flux path is $\frac{\pi}{2} (t + g)$

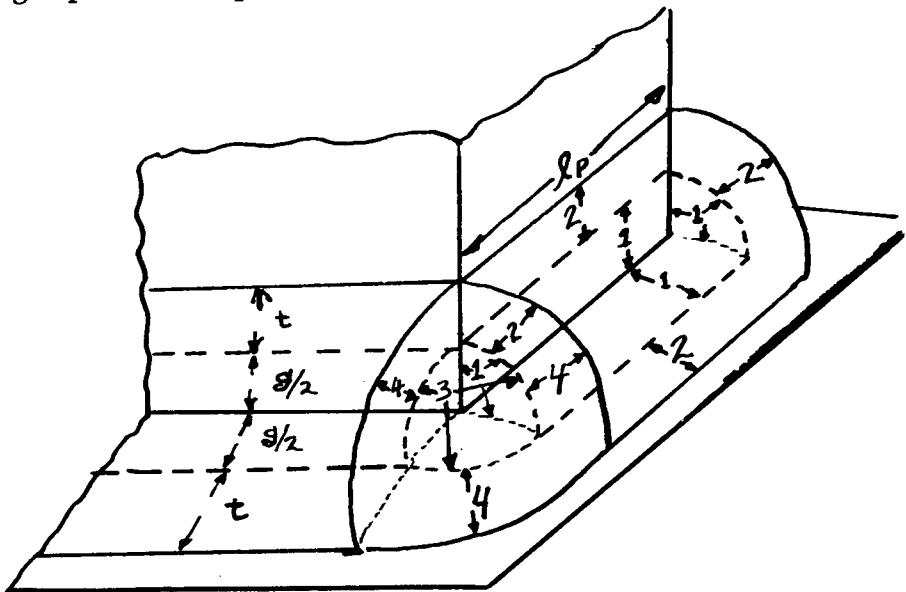
Maximum area of flux path is -

$$\frac{\pi\left(\frac{g}{2} + t\right)^2}{4} - \frac{\pi g^2}{16} = \frac{\pi}{4} (t^2 + tg)$$

Average area of path is considered to be -

$$\frac{\pi}{8} t(t+g) \text{ and } P = \frac{uA}{\lambda} = \frac{u \frac{\pi}{8} t (t+g)}{\frac{\pi}{2} (t+g)} = \frac{ut}{4}$$

Right prism and plane of infinite extent parallel to end of prism.



Simplified flux paths are designated 1, 2, 3, 4.

Path 1 --- This path is $1/2$ of the semi-circular cylinder so permeance is twice as great.

$$P = 0.52 \mu A$$

Path 2 --- This path is one half of a half annulus so permeance is twice as great.

$$P = \frac{1.28 \mu A l_p}{\left(\frac{g}{t} + 1\right)}$$

when $g < 3t$

$$P = \frac{2 \mu A l_p}{\pi} \ln \left(1 + \frac{2t}{g}\right)$$

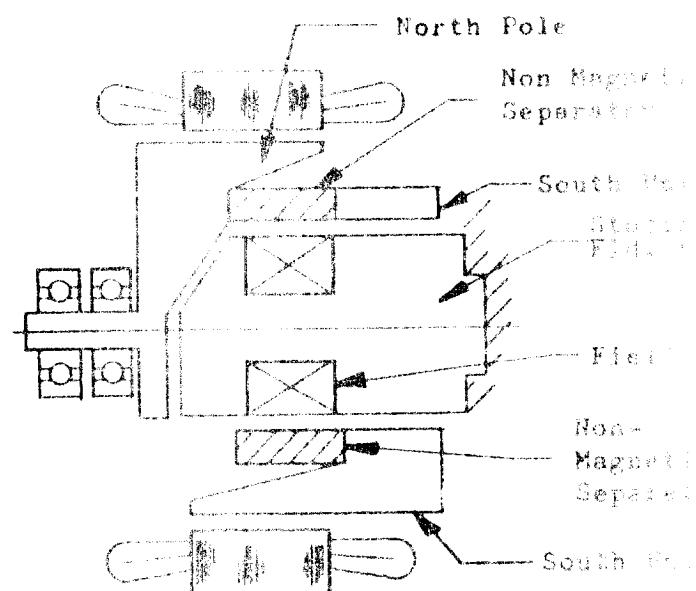
Path 3 --- This path is $1/2$ of a spherical quadrant

$$P = 0.154 \mu g$$

Path 4 --- This path is $1/2$ quadrant of a spherical shell

$$P = 0.5 \mu t$$

THE INSIDE-CORE, RADIATION-COIL DESIGN

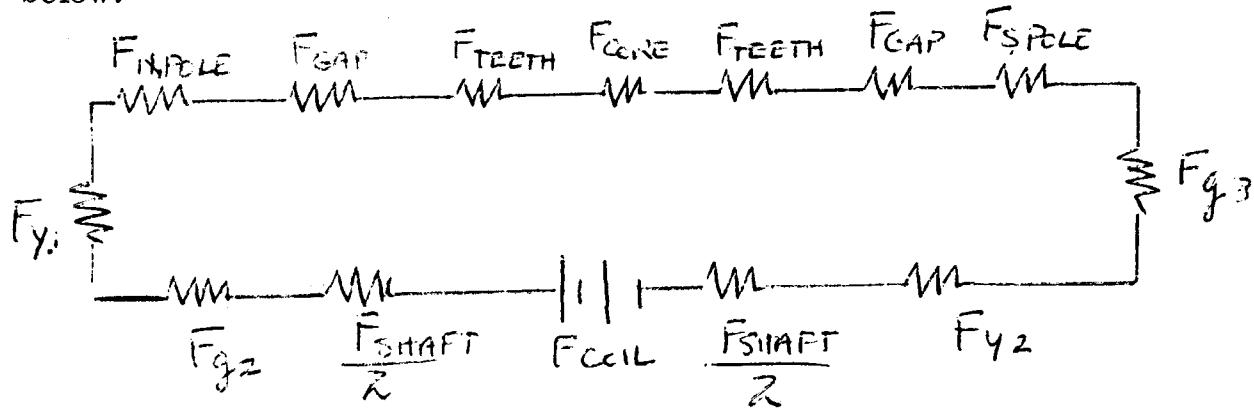


STATIONARY - COIL, INSIDE - COIL, LUNDELL GENERATOR

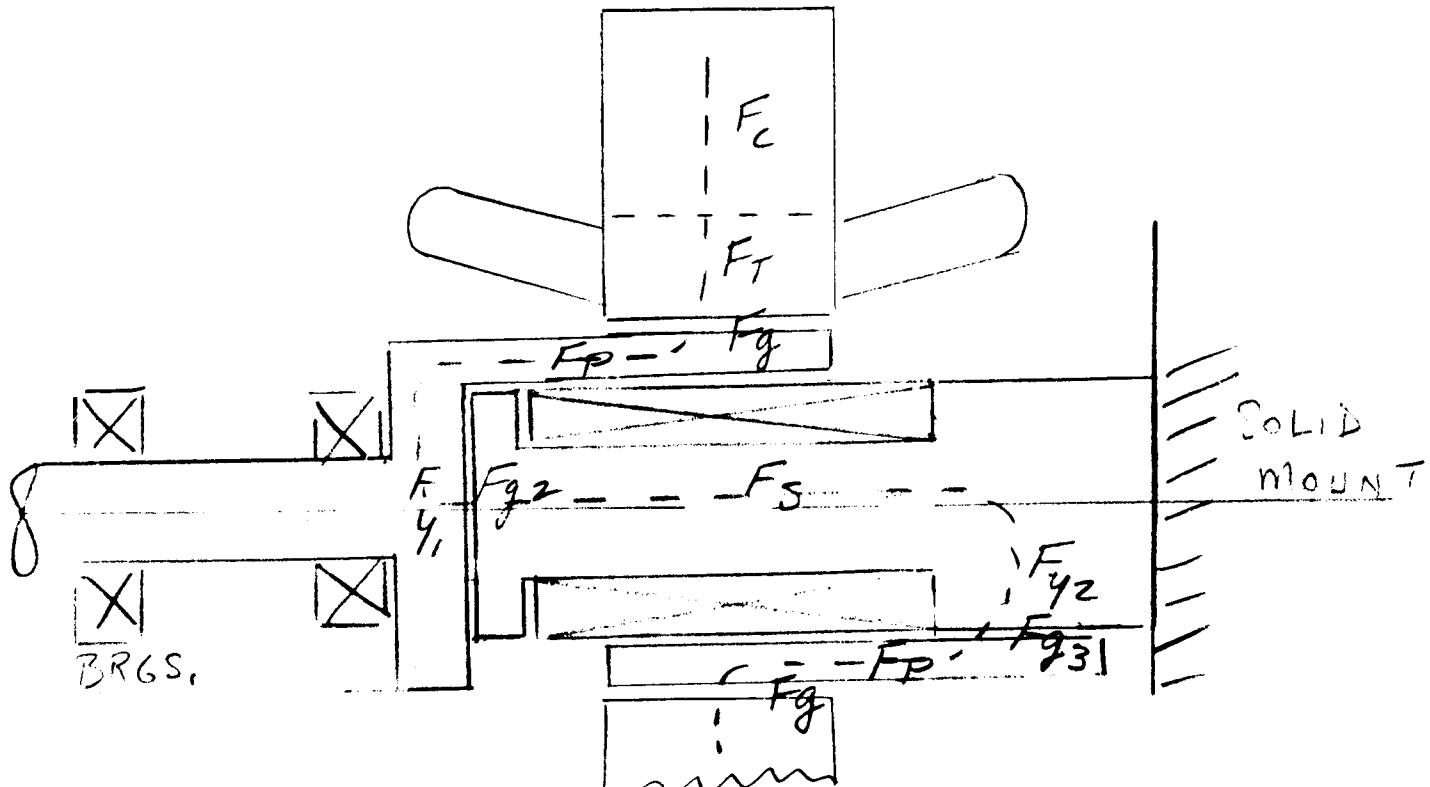
This type of generator is sold for automotive use. See Larson, "A High-Capacity, Maintenance-Free Generating System for Motor Coaches", Electrical Engineering Nov. 1959, pp 1096 - 1099.

It is brushless and could be used in some applications in space. One such application might be one requiring an overhung rotor on a small engine drive-shaft.

The flux circuit of the machine may be represented by the diagram below:



The various mmf drops are shown in the following sketch:



INSIDE-COIL, STATIONARY-COIL LUNDELL GENERATOR
COMPUTER DESIGN ----- (INPUT)

MODEL	EWO	DESIGN NO(1)	
(2)	KVA	GENERATOR KVA	RATIO MAX TO MIN OF FUND (71) C ₁
(3)	E	LINE VOLTS	WINDING CONSTANT (72) C _w
(4)	ph	PHASE VOLTS	POLE CONSTANT (73) C _p
(5)	m	PHASES	END EXTENSION ONE TURN (48) L _E
(5a)	f	FREQUENCY	DEMAGNETIZATION FACTOR (74) C _m
(6)	p	POLES	CROSS MAGNETIZING FACTOR (75) C _g
(7)	RPM	RPM	POLE EMBRACE (77) α
(8)	I _{ph}	PHASE CURRENT	WIDTH OF POLE (NARROW END) (76) b _{P1}
(9)	PF	POWER FACTOR	WIDTH OF POLE (WIDE END) (76) b _{P2}
(9a)	K _c	ADJ. FACTOR	POLE THICKNESS (NARROW END) (76) t _{P1}
(10)		OPTIONAL LOAD POINT	POLE THICKNESS (WIDE END) (76) t _{P2}
STATOR STACK	(11)	d	POLE LENGTH (76) l _P
	(12)	D	ROTOR DIAMETER (112) d _R
	(13)	l	WEIGHT OF ROTOR IRON (157) (-)
	(14)	n _v	POLE FACE LOSS FACTOR (187) K _V
	(15)	b _v	FLUX PLATE THICKNESS (78) t _{FP}
	(16)	K _i	FLUX PLATE DIAMETER (78) d _{FP}
	(19)	k	SHAFT OUT (FLUX CARRYING PORT) (78) d _S
	(20)	B	SHAFT LENGTH (FLUX CARRYING PORT) (78) l _{SW}
	(21)		PERM. OF LEAKAGE PATH 1 (80) P ₁
	(22)	b _o	PERM. OF LEAKAGE PATH 2 (81) P ₂
STATOR SLOT	(22)	b ₁	PERM. OF LEAKAGE PATH 3 (82) P ₃
	(22)	b ₂	PERM. OF LEAKAGE PATH 4 (83) P ₄
	(22)	b ₃	PERM. OF LEAKAGE PATH 5 (84) P ₅
	(22)	b _s	PERM. OF LEAKAGE PATH 7 (86) P ₇
	(22)	h _o	LENGTH OF PERM PATH 1 (80a) l ₁
	(22)	h ₁	LENGTH OF PERM PATH 2 (81a) l ₂
	(22)	h ₂	LENGTH OF PERM PATH 3 (82a) l ₃
	(22)	h ₃	OUTSIDE DIA. OF FIELD COIL (78) d _{CO}
	(22)	h _s	LENGTH OF FIELD COIL (76) l _{CO}
	(22)	h _t	NO. OF FIELD TURNS / COIL (146) N _F
STATOR WINDING	(22)	h _w	MEAN LENGTH OF FLD. TURN (147) l _{ft}
	(23)	Q	FLD. COND. DIA. OR WIDTH (148)
	(28)		FLD. COND. THICKNESS (149)
	(29)		FLD. TEMP IN °C (150) X _f °C
	(30)	n _s	RESISTIVITY OF FIELD COND @ 20° (151) ρ _f
	(31)	y	NO LOAD SAT. (87)
	(32)	c	FRICITION & WINDAGE (183) (F&W)
	(33)		STATOR LAM MATERIAL (18)
	(34)	N _{st}	POLE MATERIAL (18)
	(34a)	N' _{st}	SHAFT MATERIAL (18) -
GAP	(39)		
(35)	d _b	DIA. OF PIN	
(36)	l _{e2}	COIL EXT. STR. PORT	
(37)	h _{st}	UNINS. STRD. HT.	
(38)	h' _{st}	DIST. BTWN. C.L OF STD.	
(42a)		PHASE BELT ANGLE	
(40)	T _{sk}	STATOR SLOT SKEW	STATOR SLOT
(50)	X °C	STATOR TEMP °C	DAMPER SLOT
(51)	P _s	RES'TVY STA. COND. @ 20°C	POLE REMARKS
	(78) g ₃	AXIAL LENGTH OF GAP (g ₃)	
	(78) d _{g3}	DIAMETER AT GAP (g ₃)	
	(78) d _{g2}	DIAMETER AT GAP (g ₂)	
	(59) g	MAIN AIR GAP	
	59a g ₂	AUXILIARY GAP (g ₂)	
	59b g ₃	AUXILIARY GAP (g ₃)	

INSIDE-COIL, STATIONARY-COIL LUNDELL GENERATOR

SUMMARY OF DESIGN CALCULATIONS ----- (OUTPUT)

MODEL NO.

EWO

DESIGN NO.

STATOR	(17) (l_s)	SOLID CORE LENGTH		CARTER COEFFICIENT	(67) (K_s)	CONSTANTS
	(24) (h_c)	DEPTH BELOW SLOT		EFFECTIVE AIR GAP	(69) (g_e)	
	(26) (γ_s)	SLOT PITCH		RATIO MAX TO FUND.	(71) (C_1)	
	(27) ($\gamma_{s1/3}$)	SLOT PITCH 1/3 DIST. UP		WINDING CONST.	(72) (C_w)	
	(42) (K_{sk})	SKEW FACTOR		POLE CONST.	(73) (C_p)	
	(43) (K_d)	DIST. FACTOR		END. EXT. ONE TURN	(48) (L_E)	
	(44) (K_p)	PITCH FACTOR		DEMAGNETIZING FACTOR	(74) (C_M)	
	(45) (n_e)	EFF. CONDUCTORS		CROSS MAGNETIZING FLTR	(75) (C_q)	
	(46) (A_c)	COND. AREA		AMP COND IN	(128) (A)	
	(47) (S_s)	CURRENT DENSITY (STA.)		REACTANCE FACTOR	(129) (X)	
	(49) (ℓ_t)	1/2 MEAN TURN		LEAKAGE REACTANCE	(130) (X_L)	
	(53) (R_{ph})	COLD STA. RES. + 20°C		REACTANCE DIRECT AXIS	(131) (X_{cd})	
	(54) (R_{ph})	HOT STA. RES. + X°C		REACTANCE QUAD AXIS	(132) (X_{cq})	
	(55) (EF_{top})	EDDY FACTOR TOP		SYN REACT DIRECT AXIS	(133) (X_d)	
	(56) (EF_{bot})	EDDY FACTOR BOT		SYN REACT QUAD AXIS	(134) (X_b)	
	(62) (λ_i)	STATOR COND. PERM.		FIELD LEAKAGE REACT	(160) (X_f)	
	(63) (λ_e)	END PERM.		FIELD SELF INDUCTANCE	(161) (L_f)	
	(65) ()	WT. OF STA COPPER		UNSAT. TRANS. REACT	(166) (X_{du})	
	(66) ()	WT. OF STA IRON		SAT. TRANS. REACT	(167) (X_d)	
	(41) (γ_p)	POLE PITCH		SUB. TRANS REACT DIRECT AX.	(168) (X_d')	
FIELD	(157) (-)	WT OF ROTOR IRON		SUB. TRANS REACT QUADAX.	(169) (X_b')	
	(145) (V_r)	PERIPHERAL SPEED		NEG SEQUENCE REACT	(170) (X_2)	
	(153) (θ_{cf})	FLD COND. AREA		ZERO SEQUENCE REACT	(172) (X_0)	
	(154) (R_F)	COLD FLD RES + 20°C		OPEN CIR. TIME CONST.	(176) (T_{do})	
PERMEANCE	(155) (R_F)	HOT FLD RES + X°C		ARM TIME CONST.	(177) (T_a)	TIME CONST
	(156) (-)	WT OF FLD COPPER		TRANS TIME CONST.	(178) (T'_d)	
	(80) (P_1)	PERM OF LEAKAGE PATH 1		SUB TRAN TIME CONST.	(179) (T'_d)	
MAGNETIZATION	(81) (P_2)	PERM OF LEAKAGE PATH 2		TOTAL FLUX	(90) (ϕ_r)	
	(82) (P_3)	PERM OF LEAKAGE PATH 3		FLUX PER POLE	(93) (ϕ_p)	
	(83) (P_4)	PERM OF LEAKAGE PATH 4		GAP DENSITY (MAIN)	(95) (B_g)	
	(84) (P_5)	PERM OF LEAKAGE PATH 5		TOOTH DENSITY	(91) (B_t)	
	(86) (P_7)	PERM OF LEAKAGE PATH 7		CORE DENSITY	(94) (B_c)	
	(180) (FSC)	SHORT CIR NI		TOOTH AMPERE TURNS	(97) (F_t)	
	(181) (SCR)	SHORT AIR RATIO		CORE AMPERE TURNS	(98) (F_c)	
				GAP AMPERE TURNS (MAIN)	(96) (F_g)	

PERCENT LOAD	0	100	150	200	OPTIONAL
(ϕ_r) (100) LEAKAGE FLUX	(ϕ_{98}) (196)				
(ϕ_{FL}) (102) TOTAL FLUX/POLE	(ϕ_{PL}) (213)				
(B_p) (103) POLE DENSITY	(B_{PL}) (213)				
(B_{sh}) (113) SHAFT DENSITY	(B_{shL}) (232)				
(B_{g1}) (119) AUX GAP (83) DENSITY	(B_{g1FL}) (230)				
(B_{g2}) (122) AUX GAP (82) DENSITY	(B_{g2FL}) (224)				
(FNL) (127) TOTAL NI	(F_{NL}) (234)				
($IFNL$) (127a) FIELD AMPERES	(I_{FL}) (237)				
(S_F) (127c) CUR. DEN. FLD.	(I) (239)				
($EFNL$) (127b) FIELD VOLTS	(EF_{FL}) (238)				
(W_s) (185) STA CORE LOSS	(W_s) (185)				
(WT_{NL}) (184) STA TOOTH LOSS	(WT_{FL}) (242)				
($I^2 R_s$) (194) STATOR CU LOSS	($I^2 R_s$) (245)				
(-) (195) EDDY LOSS	(-) (246)				
(WP_{NL}) (186) POLE FACE LOSS	(WP_{FL}) (243)				
($I^2 R_F$) (182) FIELD COIL LOSS	($I^2 R_F$) (241)				
(F_{FW}) (183) FW LOSS	(F_{FW}) (183)				
(-) (196) TOTAL LOSSES	(-) (247)				
(-) (-) PERCENT EFF	(-) (251)				

INSIDE-COIL, STATIONARY-COIL LUNDELL
NO LOAD SATURATION OUTPUT SHEET

ITEMS ↓ % VOLTS →	(3) (E) VOLTS	(95) (B_g) MAIN GAP DENSITY	(122) (B_{g2}) DENSITY (g_2)	(119) (B_{g3}) DENSITY (g_3)	(94) (B_c) STA CORE DENSITY	(91) (B_t) STA. TOOTH DENSITY
	(100) (Φ_L) LEAKAGE FLUX	(102) Φ_T TOTAL FLUX/POLE	(103) B_p POLE DENSITY	(113) B_{sh} SHAFT DENSITY	(127) FNL TOTAL N.I.	—
80%						
90%						
100%						
110%						
120%						
130%						
140%						
150%						
160%						

The design manual has been arranged as a computer program and the sequence of calculations results from storage limitations of the smaller computers (1620).

A number is assigned to a symbol and maintained throughout all of the manuals presented in this Quarterly Report. Where the symbol is not used in a particular manual, the symbol and corresponding number are omitted entirely from the manual.

The symbol number in brackets wherever found means the symbol and not the value of the number itself. Numbers without brackets are numerical values.

A symbol list with corresponding design manual calculation numbers, Fortran program symbols and the definition of the symbols is given at the beginning of the manual.

The design equations in the manual are written with symbols and are repeated with the bracketed numbers that locate the symbol definition in the symbol list.

Following the design equations, the Fortran program is published with the same identifying equation numbers found in the design manual.

INSIDE-COIL, STATIONARY-COIL LUNDELL

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
<u>A, a</u>			
(128)	A	A	Ampere conductors per inch
(46)	a_c	AC	Conductor area of stator winding
(153)	a_{cf}	AS	Conductor area of field coil
(68)	A_g	GA	Main gap area
(70)	A_{g2}	A2	Auxiliary air gap (g2) area
(70a)	A_{g3}	A3	Auxiliary air gap (g3) area
(79)	a_p	AP	Pole area
(112)	a_s	AS	Area of shaft
<u>B, b</u>			
(20)	B	BK	Density
(22)	b_o	BO	Width of stator slot opening
(94)	B_c ,	BC1	Stator core density N. L.
(76)	b_{p1}	BP1	Width of pole (narrow end)
(76)	b_{p2}	BP2	Width of pole (wide end)
(95)	B_g ,	BG1	Main air gap density (N. L.)
(122)	B_{g2}	BG2	Auxiliary gap (g2) density (N. L.)
(119)	B_{g3}	BG3	Auxiliary gap (g3) density (N. L.)
(224)	$B_{g2\text{ FL}}$	BG2L	Density in auxiliary gap (g2) (F. L.)

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
(230)	B_{g3FL}	BG3L	Density in auxiliary gap (g3) (F. L.)
(103)	B_p	BP	Pole density
(213a)	B_{pl}	BPL	Flux density at base of pole
(22)	b_s	BS	Stator slot dimension per Fig. 1
(57a)	$b_t \frac{1}{3}$	SM	Stator tooth width 1/3 distance from narrowest end
(91)	B_T	BT1	Stator tooth density (N. L.)
(57)	b_{tm}	TM	Stator tooth width 1/2 distance from narrowest end
(15)	b_v	BV	Radial duct width
(113)	B_{SH}	BSH	Density in shaft (N. L.)
(232)	B_{SHL}	BSHL	Density in shaft (F. L.)
<u>C, c</u>			
(32)	c	C	Parallel paths
(71)	C_1	C1	Ratio of maximum fundamental of field form to the actual maximum of the field form
(74)	C_M	CM	Demagnetizing factor
(73)	C_P	CP	Pole constant
(75)	C_q	CQ	Cross magnetizing factor
(72)	C_W	CW	Winding constant

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
<u>D, d</u>			
(12)	D	DU	Stator lamination outside diameter
(11)	d	DI	Stator lamination inside diameter
(35)	d_b	DB	Diameter of bender pin
(78)	d_{g2}	DG2	Diameter containing gap (g2)
(78)	d_{g3}	DG3	Diameter at air gap (g3)
(78)	d_{oc}	DC1	Outside diameter of shaft
(11a)	d_r	DR	Outside rotor diameter
(78)	d_s	DS1	Diameter of shaft
<u>E, e</u>			
(3)	E	EE	Line volts
(55)	$E_{F_{TOP}}$	ET	Eddy factor top
(56)	$E_{F_{BOT}}$	EB	Eddy factor bottom
(238)	E_{FFL}	EPFL	Full load field volts
(127b)	E_{FNL}	EPNL	No load field volts
(4)	E_{PH}	EP	Phase volts
<u>F, f</u>			
(5a)	f	F	Frequency
(98)	F_c	FC	N. L. stator core ampere turns
(236)	F_{FL}	FFL	Total full load ampere turns

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation
(96)	F_g	FG	N. L. main gap ampere turns
(123)	F_{g2}	FG2	N. L. gap (g2) ampere turns
(225)	F_{g2FL}	FG2L	F. L. gap (g2) ampere turns
(120)	F_{g3}	FG3	N. L. gap (g3) ampere turns
(231)	F_{g3FL}	FG3L	F. L. gap (g3) ampere turns
(127)	F_{NL}	FNL	Total no load ampere turns
(104)	F_p	FP	Pole ampere turns
(213c)	F_{pl}	FPL	Ampere turns per pole
(180)	F_{SC}	FSC	Short circuit ampere turns
(97)	F_T	FT	N. L. stator tooth ampere turns
(183)	F & W	WF	Friction and windage
(114)	F_{SH}	FSH	N. L. shaft ampere turns
(233)	F_{SHL}	FSHL	F. L. shaft ampere turns

G, g

(59)	g	GC	Main air gap
(59a)	g_2	G2	Auxiliary air gap
(59c)	g_3	G3	Auxiliary air gap
(69)	g_e	GE	Effective main gap

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
<u>H, h</u>			
(24)	h_c	HC	Depth below slot
(38)	h_{ST}'	SD	Distance between center line of strand in depth
(39)	h_{ST}	SH	Stator coil strand thickness (largest dimension)
<u>I, i</u>			
(237)	I_{FFL}	AIFL	F. L. field current
(127a)	I_{FNL}	AINL	N. L. field current
(8)	I_{PH}	PI	Phase current
(182)	$I^2 R_F$	FEL	N. L. field coil loss
(241)	$I^2 R_{FL}$	FCUL	F. L. coil copper loss
(194)	$I^2 R$	PS	N. L. stator copper loss
(245)	$I^2 R_S$	SCUL	F. L. stator copper loss
<u>K, k</u>			
(19)	k	WL	Watts/lb core loss
(9a)	K_c	CK	Adjustment factor
(43)	K_d	DF	Distribution factor
(63)	K_e	EK	Leakage reactive facto.
(16)	K_i	SF	Stacking factor
(44)	K_p	CF	Pitch factor

Calculation Number	Electrical Symbol	Fortran Symbol	Explanation
(67)	K_S	CC	Carter coefficient
(42)	K_{SK}	FS	Skew factor
(2)	K_{VA}	VA	Generator rating
(61)	K_X	FF	Factor to account for difference in phase current in coil sides in same slot

L, l

(13)	ℓ	CL	Gross core length (stator)
(80a)	ℓ_1	AL1	Length of leakage path 1
(81a)	ℓ_2	AL2	Length of leakage path 2
(82a)	ℓ_3	AL3	Length of leakage path 3
(76)	ℓ_{co}	ALCO	Length of coil
(48)	L_E	EL	Stator coil end extension length
(36)	ℓ_{e2}	CE	Coil extension beyond core
(161)	L_F	SI	Field inductance
(78)	ℓ_{g3}	ALG3	Length of auxiliary gap (g3)
(17)	ℓ_g	SS	Solid core length
(49)	ℓ_t	HM	1/2 mean turn (stator coil)
(147)	ℓ_{tf}	FE	1/2 mean turn of field coil
(78)	ℓ_{SH}	ALSH	Effective length of shaft

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
<u>M, m</u>			
(5)	m	PN	No. of phases
<u>N, n</u>			
(146)	n_f	PT	Field turns per coil
(45)	n_e	EC	Effective conductors
(30)	n_s	SC	Conductors per slot
(34)	N_{ST}	SN	Strands per conductor in depth
(34a)	N'_{ST}	SN1	Strands per conductor (total)
(14)	n_v	HV	Radial ducts
<u>P, p</u>			
(6)	p	PX	No. of poles
(9)	PF	PF	Power factor
(80)	P_1	P1	Permeance of leakage path 1
(81)	P_2	P2	Permeance of leakage path 2
(82)	P_3	P3	Permeance of leakage path 3
(83)	P_4	P4	Permeance of leakage path 4
(84)	P_5	P5	Permeance of leakage path 5
(86)	P_7	P7	Permeance of leakage path 7
<u>Q, q</u>			
(23)	Q	QQ	No. of slots
(25)	q	QN	Slots per pole per phase

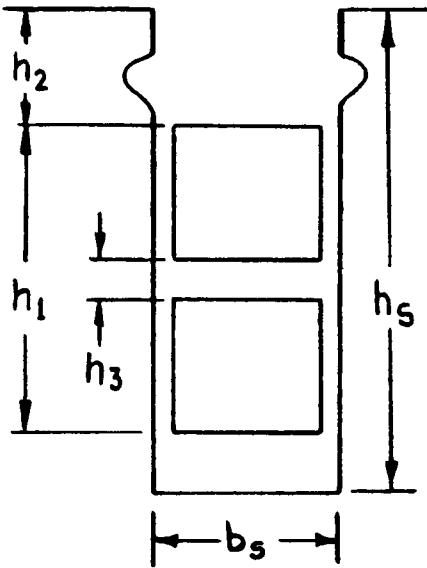
<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
(154)	R_f (cold)	FK	Cold field resistance at 20 °C
(155)	R_f (hot)	FR	Hot field resistance at X °C
(7)	RPM	RPM	Revolutions per minute
(53)	R_{SPH} (cold)	RG	Stator resistance per phase at 20 °C
(54)	R_{SPH} (hot)	RP	Stator resistance per phase at X °C
<u>S, s</u>			
(181)	SCR	SCR	Short circuit ratio
(127c)	s_F	CD	Current density in field conductor
(47)	s_S	S	Current density in stator conductor
<u>T, t</u>			
(177)	T_a	TA	Armature time constant
(178)	T_d'	T5	Transient time constant
(176)	T_{do}'	TC	Open circuit time constant
(76)	t_{p1}	TP1	Thickness of pole (narrow end)
(76)	t_{p2}	TP2	Thickness of pole (wide end)
<u>V, v</u>			
(145)	v_r	VR	Peripheral speed
<u>W, w</u>			
(185)	w_C	WQ	Stator core loss
(186)	w_{NPL}	WN	N. L. pole face loss

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
(243)	W_{PFL}	WNL	F. L. pole face loss
(242)	W_{TFL}	WTFL	F. L. stator teeth loss
(184)	W_{TNL}	WT	N. L. stator teeth loss
<u>X, x</u>			
(129)	X	XR	Reactance factor
(131)	X_{ad}	XD	Reactance direct axis
(132)	X_{aq}	XQ	Reactance quadrature axis
(133)	X_d	XA	Synchronous reactance - direct axis
(167)	X'_d	XS	Saturated transient reactance
(168)	X''_d	XX	Subtransient reactance direct axis
(166)	X'_{du}	XU	Unsaturated transient reactance
(160)	X'_F	XF	Effective field leakage reactance
(150)	X_f °C	T2	Expected field temperature at full load
(130)	X_ℓ	XL	Leakage reactance
(169)	X''_q	XY	Subtransient reactance quadrature axis
(134)	X_q	XB	Synchronous reactance quadrature axis
(50)	X_s °C	TI	Stator expected temperature at F. L.
(170)	X_2	XN	Negative sequence reactance
(172)	X_o	XO	Zero sequence reactance

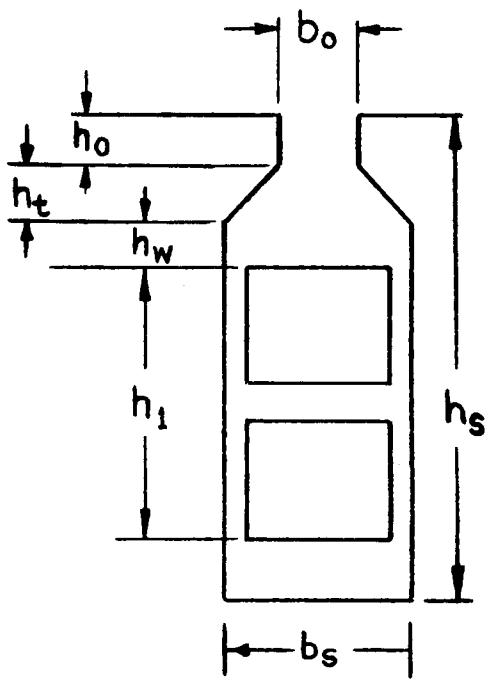
<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
	<u>Y, y</u>		
(31)	y	YY	Throw or coil span
(108)	\emptyset_{g2}	PG2	
(100)	\emptyset_L	PL	Rotor leakage flux
(221)	\emptyset_{g2}	PG2 L	Flux in auxiliary gap (g2) at F. L.
(118)	\emptyset_{L5}	PL5	N. L. leakage flux in Path 5
(99)	\emptyset_{L7}	PL7	N. L. leakage flux in Path 7
(196a)	\emptyset_{LL}	PLL	Leakage flux per pole
(226)	\emptyset_{5L}	PL5 L	F. L. leakage flux in Path 5
(207)	\emptyset_{7L}	PL7 L	F. L. leakage flux in Path 7
(92)	\emptyset_p	FQ	Flux per pole N. L.
(213)	\emptyset_{PL}	FQL	Flux per pole F. L.
(102)	\emptyset_{PT}		Total flux per pole
(213a)	\emptyset_{PTL}	PTLL	Total flux per pole
(111)	\emptyset_{SH}	PSH	Shaft flux N. L.
(88)	\emptyset_T	TG	Total flux N. L.
	<u>τ</u>		
(41)	τ_p	TP	Pole pitch
(26)	τ_s	TS	Stator slot pitch
(40)	τ_{SK}	SK	Stator slot skew
(27)	$\tau_{S1/3}$	TT	Stator slot pitch 1/3 distance from narrowest section of tooth

<u>Calculation Number</u>	<u>Electrical Symbol</u>	<u>Fortran Symbol</u>	<u>Explanation</u>
		<u>λ</u>	
(64)	λ_E	EW	End Winding permeance
(159)	λ_{pt}	BE	Permeance of end portion of damper bar
(62)	λ_i	PC	Conductor permeance
		<u>ρ</u>	
(151)	ρ_f	RR	Resistivity of field conductor at 20 °C
(152)	ρ_f (hot)		Resistivity of field conductor at expected temperature at F. L.
(51)	ρ_s	RS	Resistivity of stator winding at 20 °C
(52)	ρ_s (hot)		Resistivity of stator winding at X °C
		<u>α</u>	
(77)	α	PE	Pole embrace

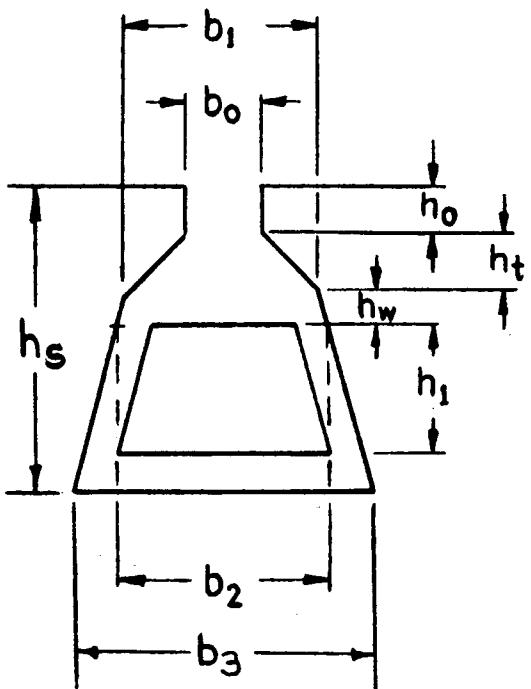
(a) Open Slots



(b) Constant Slot Width



(c) Constant Tooth Width



(d) Round Slots

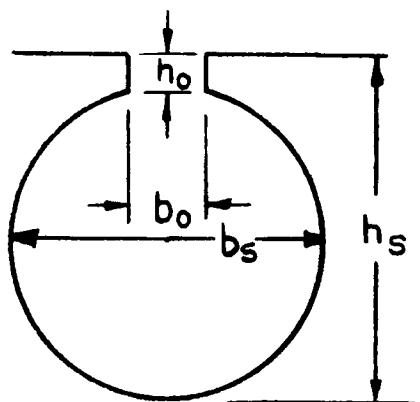


FIG 1

VALUES OF K_{dn} FOR INTEGRAL-SLOT, 30 WINDINGS - TABLE 2

n	K_{dn} - HARMONIC DISTRIBUTION FACTORS									
$q =$	2	3	4	5	6	7	8	9	10	∞
1	.966	.960	.958	.957	.957	.957	.956	.955	.955	.955
3	.707	.667	.654	.646	.644	.642	.641	.640	.639	.636
5	.259	.217	.205	.200	.197	.195	.194	.194	.193	.191
7	-.259	-.177	-.158	-.149	-.145	-.143	-.141	-.140	-.140	-.136
9	-.707	-.333	-.270	-.247	-.236	-.229	-.225	-.222	-.220	-.212
11	-.966	-.177	-.126	-.110	-.102	-.097	-.095	-.093	-.092	-.087
13	-.966	.217	.126	.102	.092	.086	.083	.081	.079	.073
15	-.707	.667	.270	.200	.172	.158	.150	.145	.141	.127
17	-.259	.960	.158	.102	.084	.075	.070	.066	.064	.056
19	.259	.960	-.205	-.110	-.084	-.072	-.066	-.062	-.060	-.059
21	.707	.667	-.654	-.247	-.172	-.143	-.127	-.118	-.112	-.091
23	.966	.217	-.958	-.149	-.092	-.072	-.063	-.057	-.054	-.041
25	.966	-.177	-.958	.200	.102	.075	.063	.056	.052	.038
27	.707	-.333	-.654	.646	.236	.158	.127	.111	.101	.071
29	.259	-.177	-.205	.957	.145	.086	.066	.056	.050	.033
31	-.259	.217	.158	.957	-.197	-.097	-.070	-.057	-.050	-.031

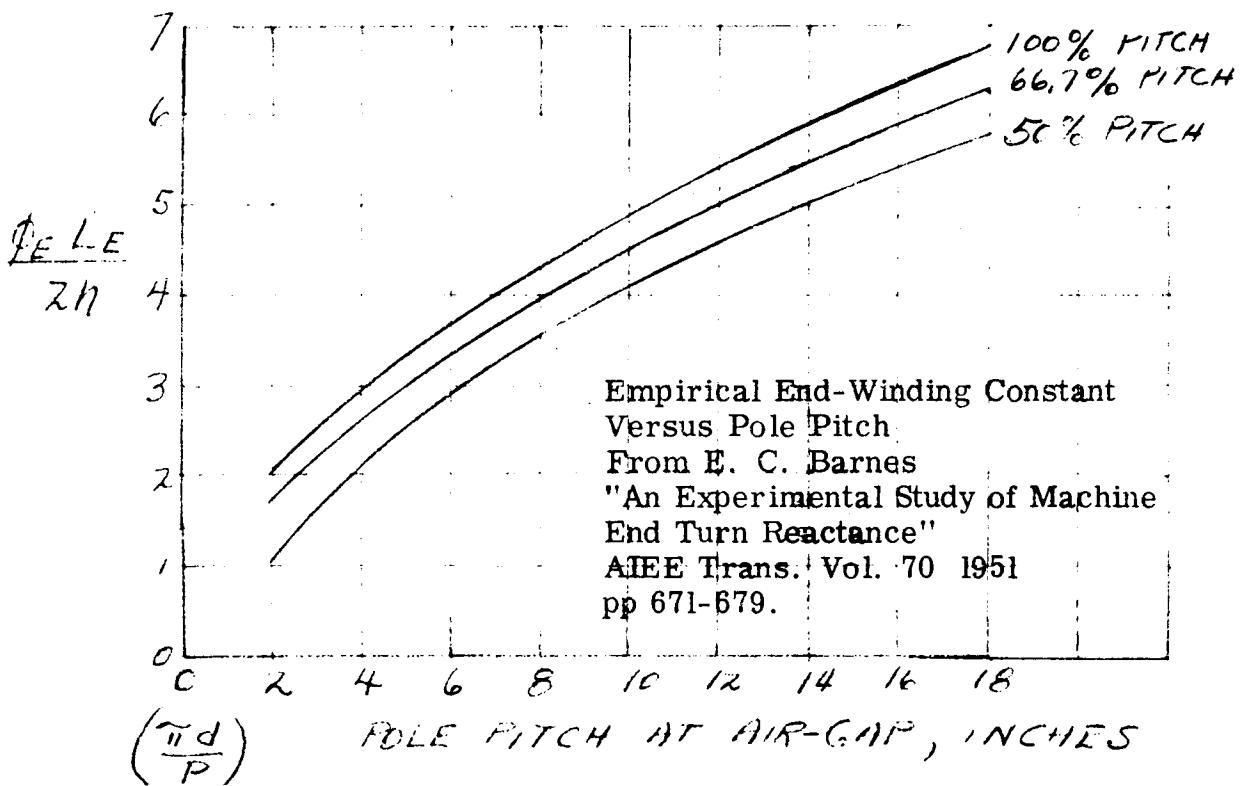
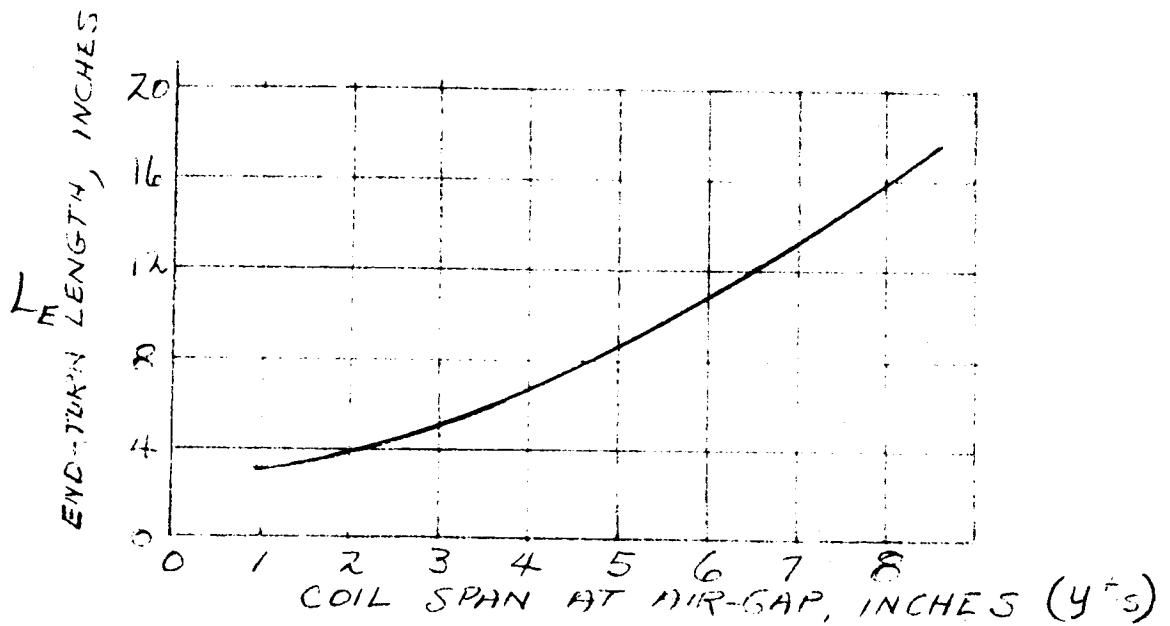
33	-.707	.667	.270	.646	-.644	-.229	-.150	-.118	-.101	-.058
35	-.966	.960	.126	.200	-.957	-.143	-.083	-.062	-.052	-.027
37	-.966	.960	-.126	-.199	-.957	.195	.095	.066	.054	.026
39	-.707	.667	-.270	-.247	-.644	.642	.225	.145	.112	.099
41	-.259	.217	-.158	-.110	-.197	.957	.141	.081	-.060	.023
43	.259	-.177	.205	.102	.145	.957	-.194	-.093	-.064	-.022
45	.707	-.333	.654	.200	.236	.642	-.641	-.222	-.141	-.042
47	.966	-.177	.958	.102	.102	.195	-.956	-.140	-.079	-.020
49	.966	.217	.958	-.110	-.092	-.143	-.956	.194	.092	.019
51	.707	.667	.654	-.247	-.172	-.229	-.641	.640	.220	.038
53	.259	.960	.205	-.149	-.084	-.097	-.194	.955	.140	.018
55	-.259	.960	-.158	.200	.084	.086	.141	.955	-.193	-.017
57	-.707	.667	-.270	.646	.172	.158	.225	.640	-.639	-.033
59	-.966	.217	-.126	.957	.092	.075	.095	.194	-.955	-.016
61	-.966	-.177	.126	.957	-.102	-.072	-.083	-.140	-.955	.016
63	-.707	-.333	.270	.646	-.236	-.143	-.150	-.222	-.639	.030
65	-.259	-.177	.158	.200	-.145	-.072	-.070	-.093	-.193	.015

ROUND COPPER WIRE

TABLE 3

SIZE AWG	BARE DIAMETER	AREA IN ²	$\Omega /1000'$ $@ 25^\circ C$	SINGLE FORMVAR	HEAVY FORMVAR	SINGLE GLASS FORMVAR	BARE WT. # /1000'	SINGLE GLASS SILICONE	DOUBLE GLASS SILICONE
36	.0050	.0000196	424	.0056	.0060		.0757		
35	.0056	.0000246	338	.0062	.0066		.0949		
34	.0063	.0000312	266	.0070	.0074		.1201		
33	.0071	.0000396	210	.0079	.0084		.1526		
32	.0080	.0000503	165	.0088	.0094	.0121	.1937		
31	.0089	.0000622	134	.0097	.0104	.0130	.2398		
30	.0100	.0000785	106	.0108	.0116	.0142	.3025	.0132	.0152
29	.0113	.000100	83.1	.0122	.0130	.0156	.3866	.0145	.0165
28	.0126	.000125	66.4	.0135	.0144	.0169	.4806	.0158	.0178
27	.0142	.000158	52.6	.0152	.0161	.0186	.6101	.0174	.0194
26	.0159	.000199	41.7	.0169	.0179	.0203	.7650	.0191	.0211
25	.0179	.000252	33.0	.0190	.0200	.0224	.970	.0211	.0231
24	.0201	.000317	26.2	.0213	.0223	.0263	1.223	.0251	.0276
23	.0226	.000401	20.7	.0238	.0249	.0289	1.546	.0276	.0301
22	.0254	.000507	16.4	.0266	.0277	.0317	1.937	.0303	.0328
21	.0285	.000638	13.0	.0299	.0310	.0349	2.459	.0335	.0360
20	.0320	.000804	10.3	.0334	.0346	.0384	3.099	.0370	.0395
19	.0360	.00102	8.14	.0374	.0386	.0424	3.900	.0409	.0434
18	.0403	.00126	6.59	.0418	.0431	.0468	4.914	.0453	.0478
17	.0453	.00159	5.22	.0469	.0482	.0519	6.213	.0503	.0528
16	.0508	.00204	4.07	.0524	.0538	.0575	7.812	.0558	.0583
15	.0571	.00255	3.26	.0588	.0602	.0639	9.87	.0621	.0646
14	.0641	.00322	2.58	.0659	.0673	.0710	12.44	.0691	.0716
13	.072	.00407	2.04	.0738	.0753	.0789	15.69	.0770	.0795
12	.0808	.00515	1.61	.0827	.0842	.0877	19.76	.0858	.0883
11	.0907	.00650	1.28	.0927	.0942	.0977	24.90	.0957	.0982
10	.102	.00817	1.02	.1039	.1055	.1089	31.43	.1069	.1094
9	.114	.0102	.814	.1165	.1181	.1225	39.62	.1204	.1254
8	.129	.0131	.634	.1306	.1323	.1366	49.98	.1345	.1395
7	.144	.0163	.510	.1465	.1482	.1525	63.03	.1503	.1553
6	.162	.0206	.403	.1643	.1661	.1703	79.44	.1680	.1730
5	.182	.0260	.319	.1842	.1861	.1902	100.2	.1879	.1929
4	.204	.0327	.254				126.3	.2103	.2153
3	.229	.0412	.202				159.3		
2	.258	.0523	.159				200.9		
0	.325	.0830	.100						
2/0	.365	.105	.0791						
4/0	.460	.166	.0500						

CURVE 1



CURVE 2

From Kennard and Spooner "Surface Iron Losses with Respect to Laminated Materials", Trans. AIEE, Vol. 43, 1924,
pp 262-281.

REFER TO ITEM (150) IN SALIENT POLE DESIGN MANUAL FOR
SAMPLE USE OF THIS CURVE

POLE FACE LOSS WATTS = $W_s \cdot K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5 \cdot K_6 \cdot \text{BORE AREA}$

$K_1 = 1.75$ FOR .063" THICK LOW C STEEL

= 7.0 FOR SOLID POLE

= 3.50 FOR .125" THICK LOW C STEEL

= 1.17 FOR .028" THICK LOW C STEEL

B_{sf} = GAP DENSITY KILOLINES / SQ IN

b_{se} = SLOT WIDTH = 6.0 for partially closed slots

G = AIR GAP (ACTUAL)

C₁ = FUNDAMENTAL OF FIELD FORM

$$C_1 = \left(\frac{\text{RPM}}{60} \right) \cdot (\text{SLOTS})^2 \cdot \text{SLOT FREQUENCY}$$

T_s = slot pitch

BORE AREA = πd^2

E_{sf} = (B_{sf})² / (8π)

UPPER SCALE X 10

E_{sf} = (B_{sf})² / (8π)

UPPER SCALE X 10

E_{sf} = (B_{sf})² / (8π)

UPPER SCALE X 10

E_{sf} = (B_{sf})² / (8π)

UPPER SCALE X 10

E_{sf} = (B_{sf})² / (8π)

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UPPER SCALE X 10

E_{sf} = (B_{sf})² / (8π)

UPPER SCALE X 10

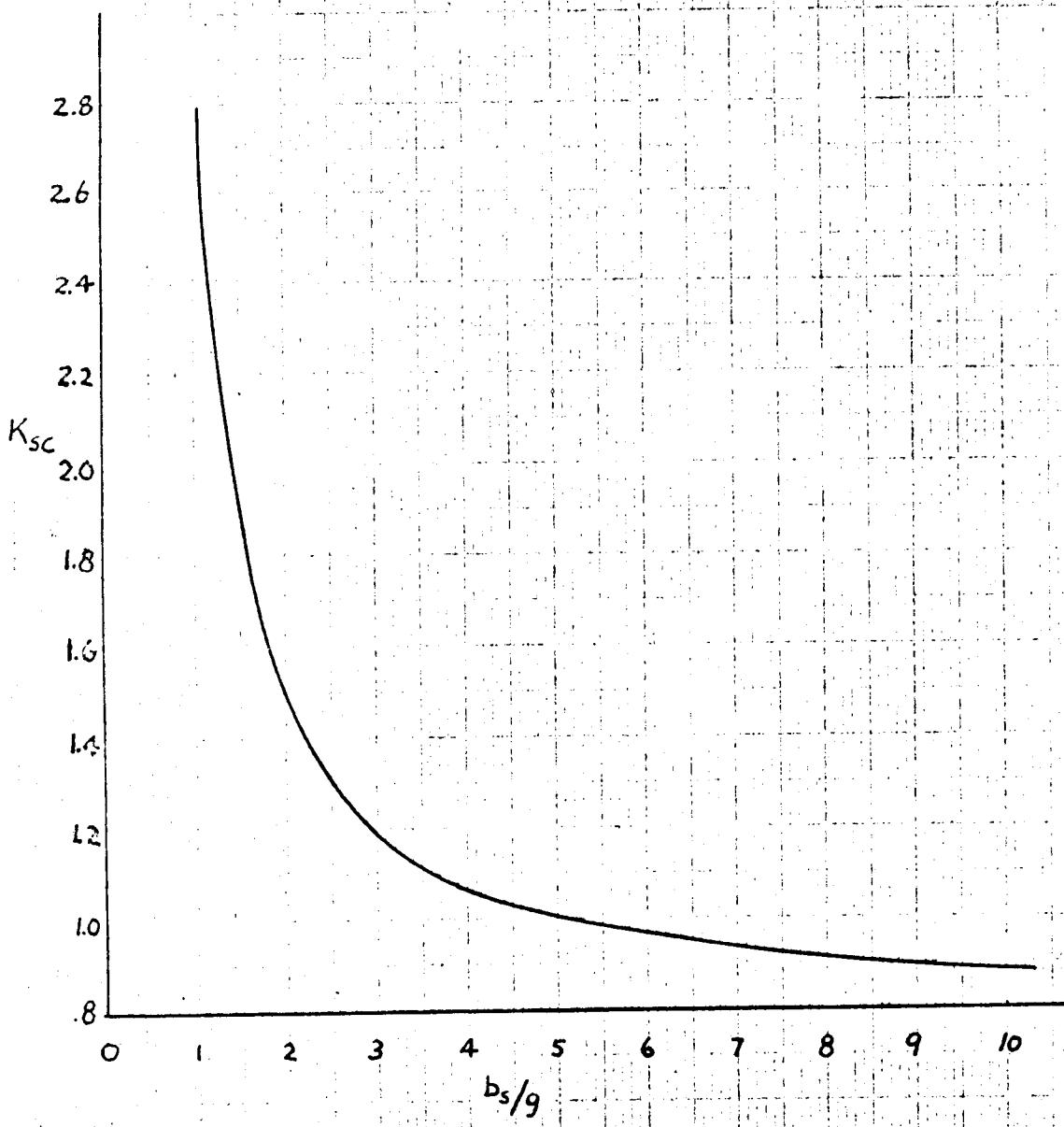
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J.A.T.

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2

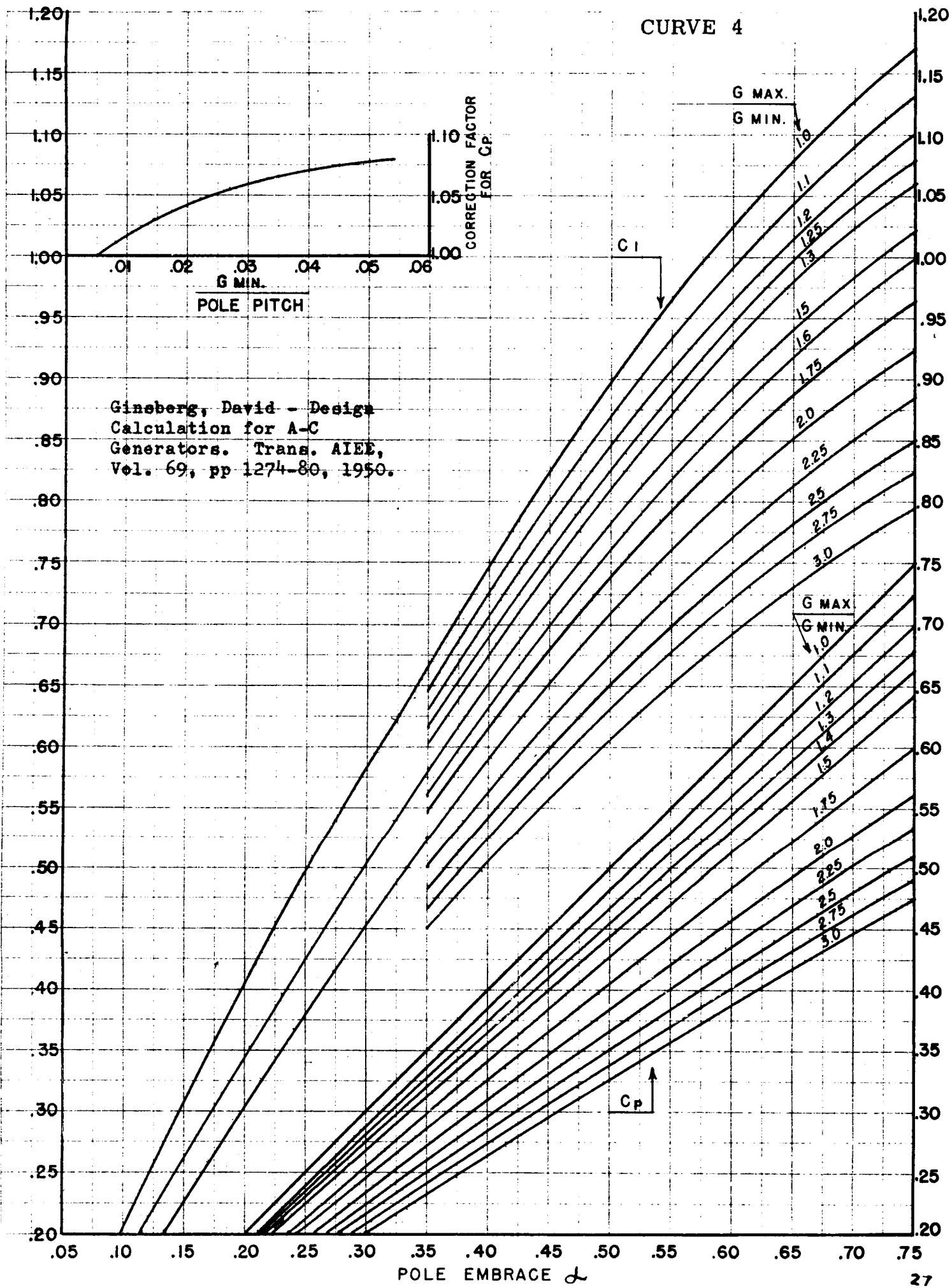
4

CURVE-3

FROM E.I. POLLARD'S "LOAD LOSSES IN SALIENT POLE
SYNCHRONOUS MACHINES" AIEE TRANS. VOL. 54
1935 PP 1332~1340



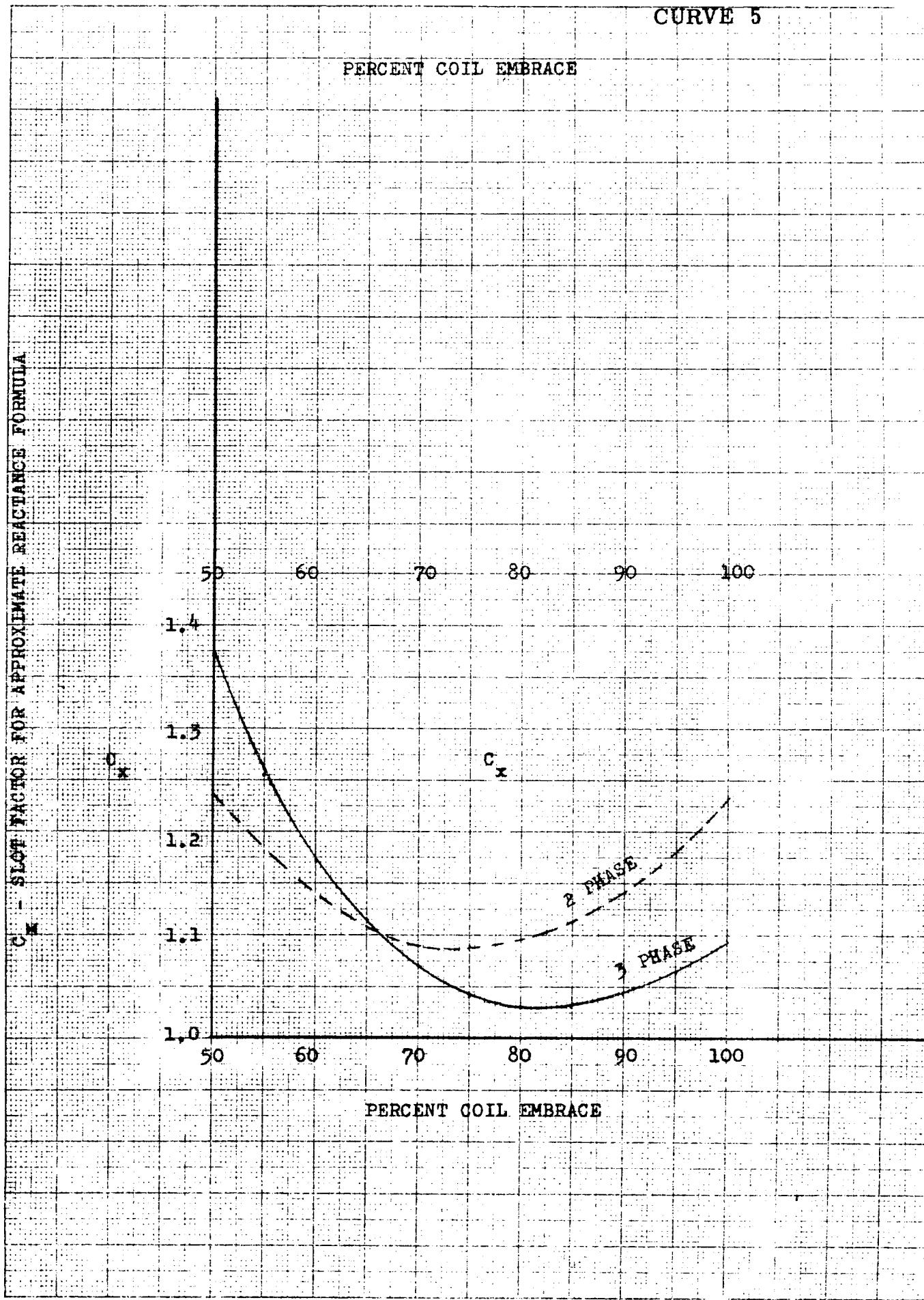
CURVE 4



CURVE 5

PERCENT COIL EMBRACE

$C_x = \text{Slope factor for approximate reactance formula}$



NO-LOAD DAMPER LOSS

CURVE 7

$$D.L. = \frac{1.246 P n_0 b P}{10^6 A_b} \left[I_s B_g K_g K_g \right] \left[\frac{\lambda_s / K_F / K_W}{(2\lambda_s + \lambda_g)} \right]^2 + \left[\frac{K_F_2 / K_W_2}{(2\lambda_s + \lambda_g)} \right]^2$$

= LOSS IN KW

$$\lambda_s = \frac{hr}{b_r} + \lambda_e + \lambda_c$$

a_b = BAR AREA IN SQ IN.

n_b = BARS/POLE

$$\lambda_g = \frac{I_b}{K_g g} = \frac{I_b}{g'}$$

P = NO. POLES

I_b = LENGTH BAR IN.

K_g = CARTER'S COEFFICIENT (TOTAL)

$K_P = f_n(b_s/g)$, CURVE (a) ($b_s = b_o$ for partially closed slots)

K_{F_1} AND $K_{F_2} = f_n(f_s/f)$ CURVE (b)

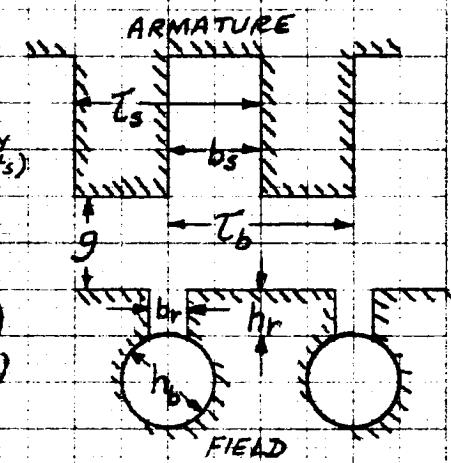
ρ = DAMPER BAR RESISTIVITY
(MICROHMS PER CU. IN.)

K_W_1 AND $K_W_2 = f_n(b_s/I_b)$, CURVE (C₁) AND (C₂)

K_{ϕ_1} AND $K_{\phi_2} = f_n(I_b/I_b)$, CURVE (d₁) AND (d₂)

$\lambda_e = f_n(b_r/g K_g)$, CURVE (e)

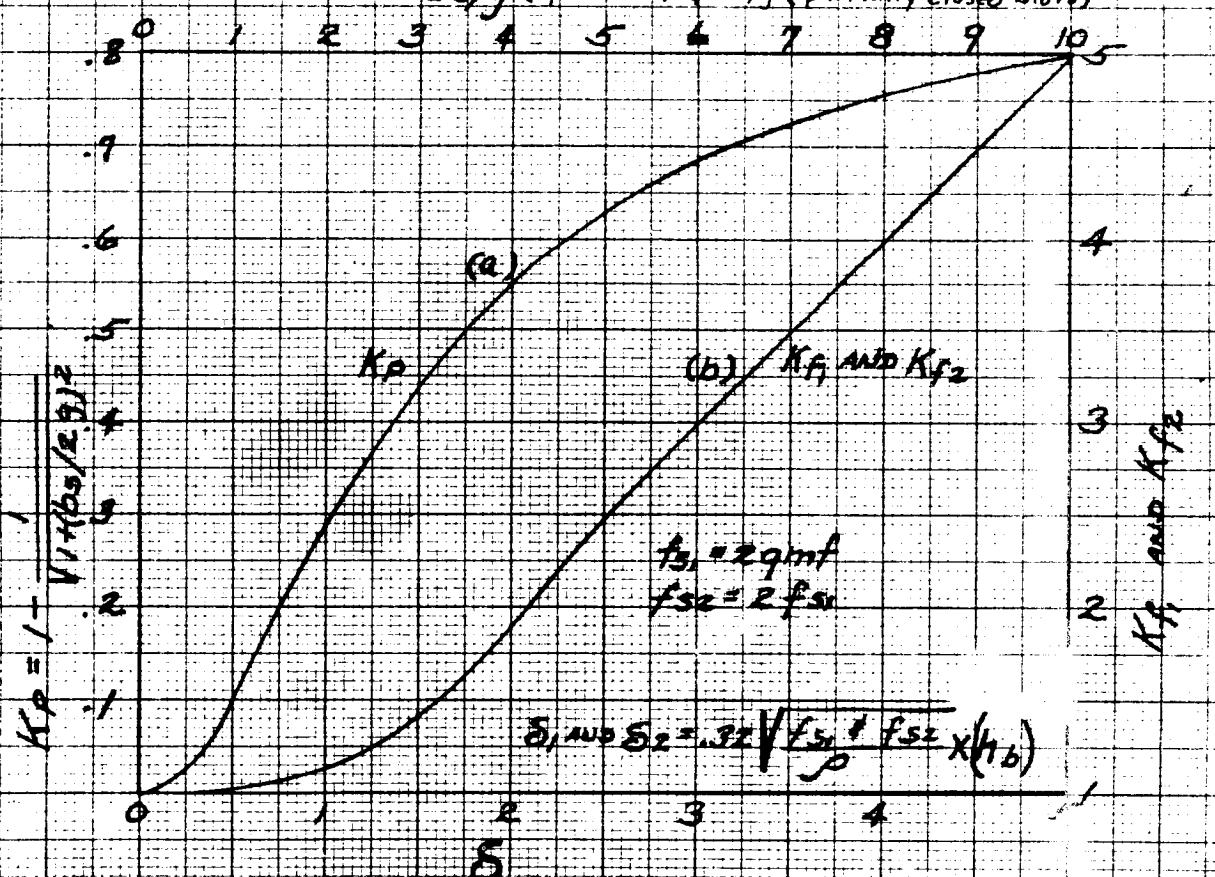
B_g IS IN HENRIES PER 50 INCH



$$\lambda_e = \frac{.75}{A_f} \quad (\text{FOR ROUND OR } 50 \text{ BARS})$$

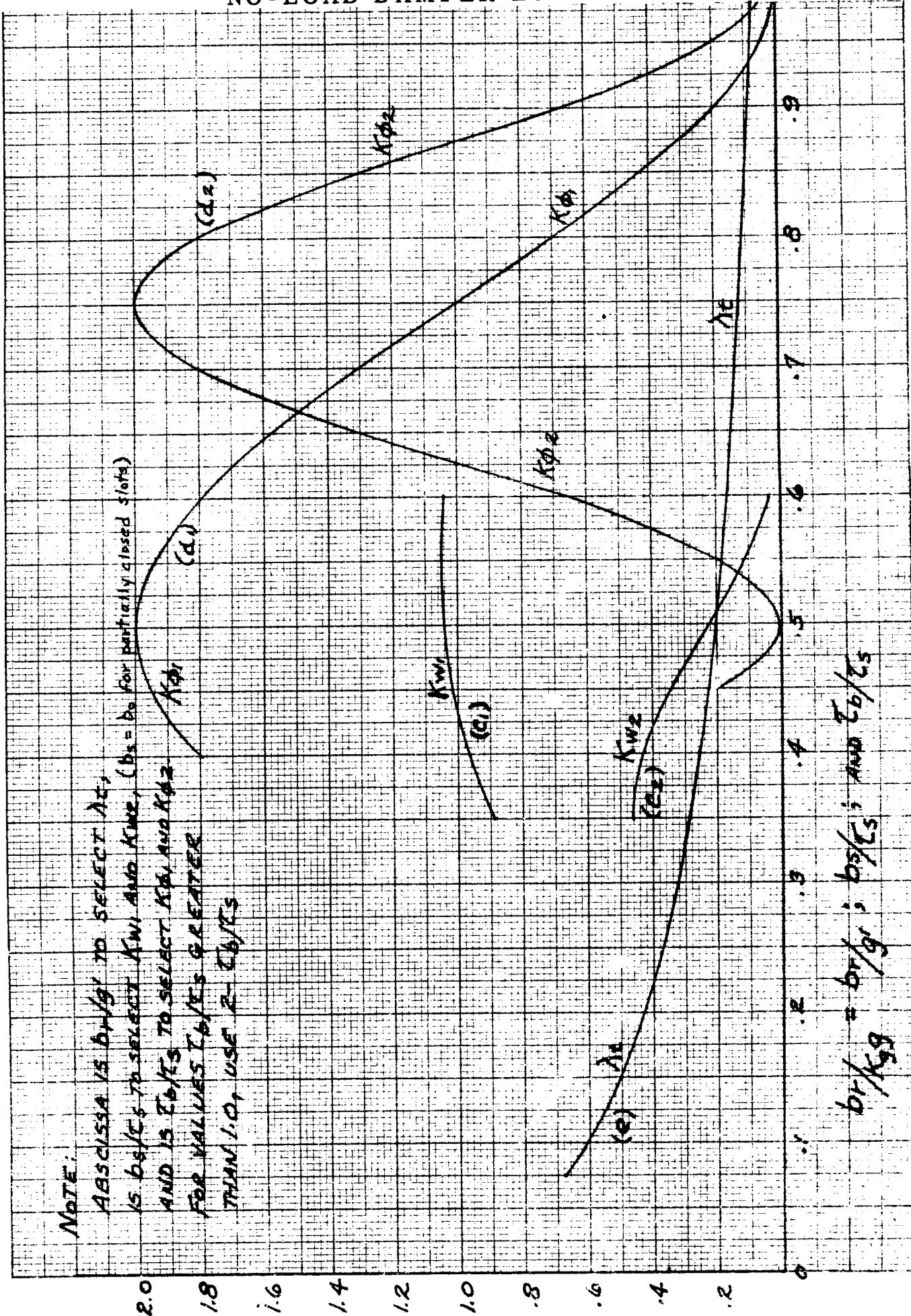
$$\lambda_e = \frac{h_r}{3b_b K_F} \quad (\text{FOR RECT. BARS})$$

b_s/g (open slots) & b_r/g (partially closed slots)



NO-LOAD DAMPER LOSS

CURVE 8



CURVE 9

PERCENT POLE EMBRACE

50

60

70

80

90

1.0

.8

.6

.4

.2

.0

C_m
&
 $C_{q'}$

K-2
10 X 10 CM.
KEUFFEL & ESSER CO., MADE IN U.S.A.

CONCENTRIC
AVG POLE SHAPE

SINE WAVE POLE

50

60

70

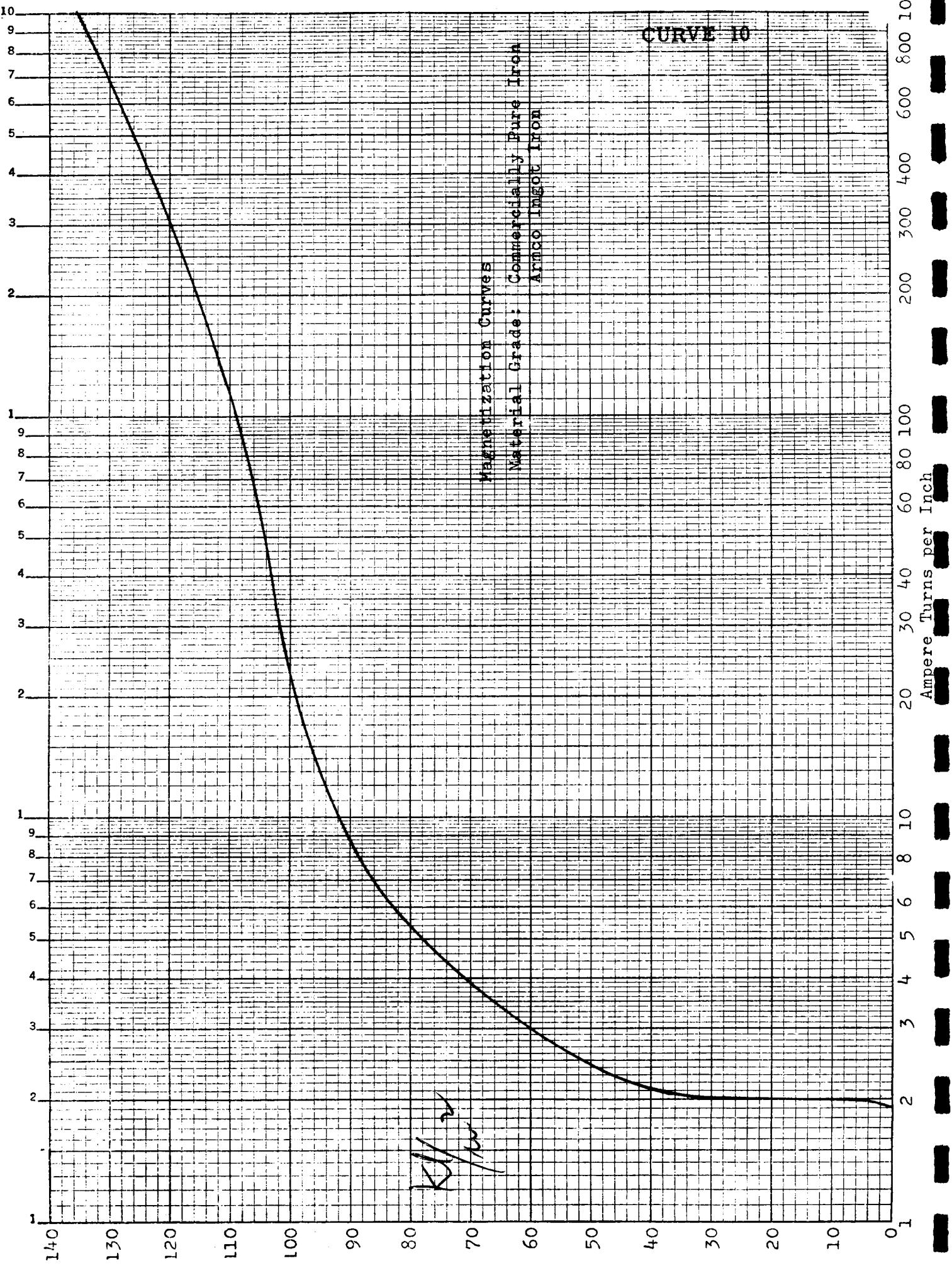
80

90

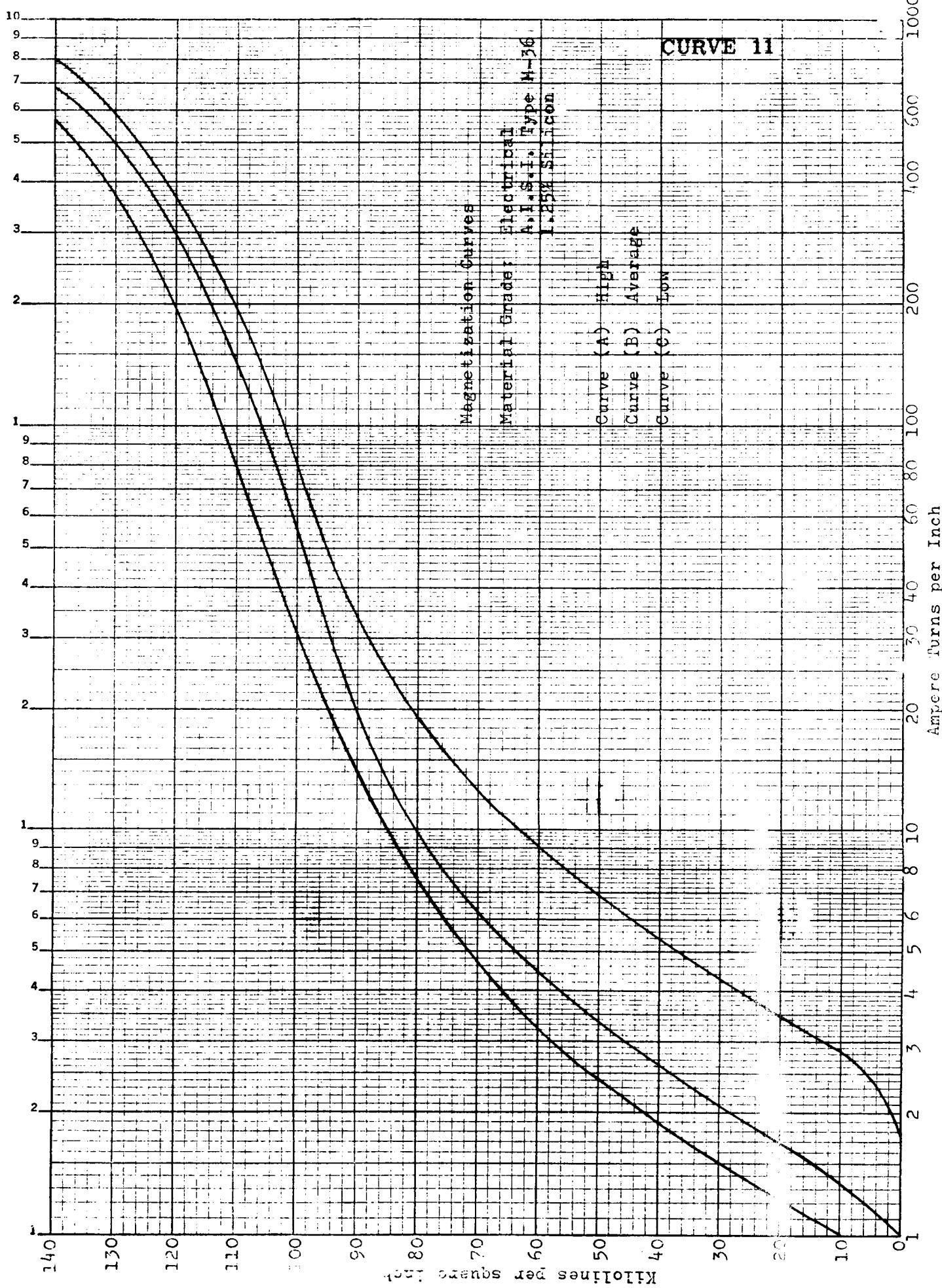
PERCENT POLE EMBRACE

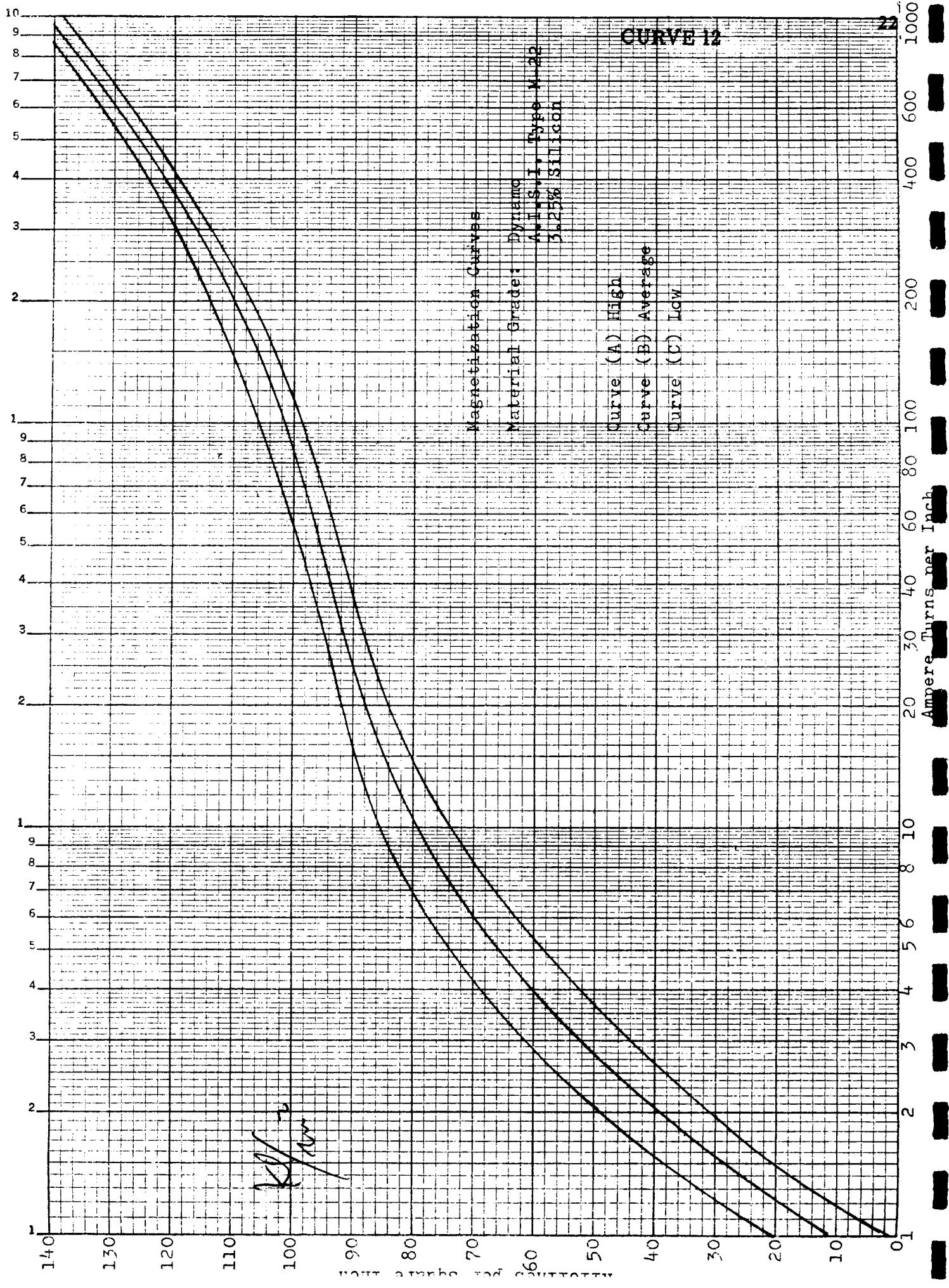
SALIENT POLE MACHINE CONSTANTS

C_m $C_{q'}$

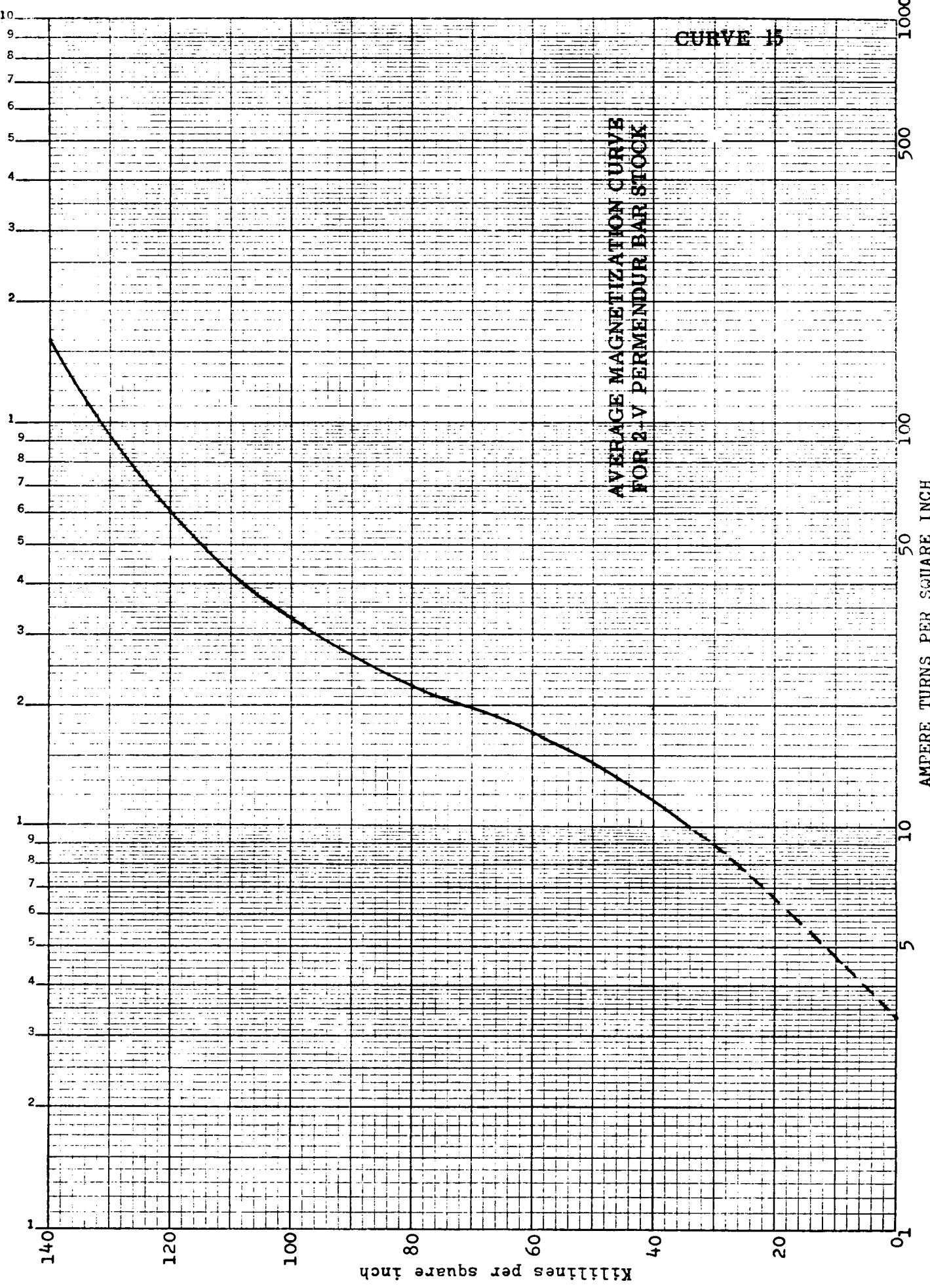


LOGARITHMIC
KELFEL & LEESEY CO.
3 CYCLES X 20 DIVISIONS

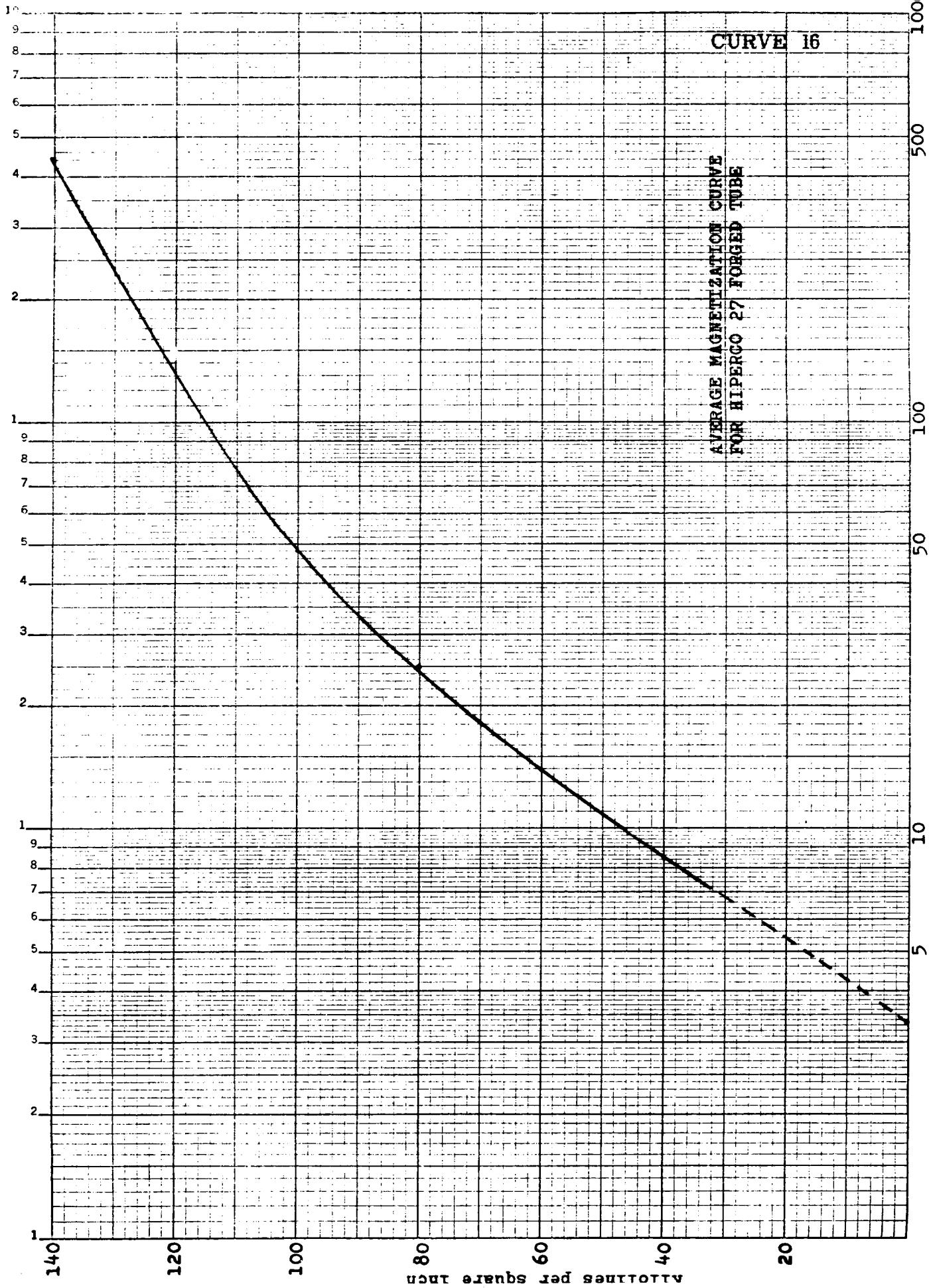




KELVIN SEMI-LOGARITHMIC
KURTZ & LESSER CO. 359-71
3 CYCLES X 70 DIVISIONS



K SEMI-LOGARITHMIC
KEUFFEL & ESSER CO.
1 CYCLE X 70 DIVISIONS



INSIDE-COIL, STATIONARY-COIL, LUNDELL, A.C. GENERATOR

(1)	--	<u>DESIGN NUMBER</u> - To be used for filing purposes
(2)	KVA	<u>GENERATOR KVA</u>
(3)	E	<u>LINE VOLTS</u>
(4)	E_{PH}	<u>PHASE VOLTS</u> - For 3 phase,  connected generator $E_{PH} = \frac{(\text{Line Volts})}{\sqrt{3}} = \frac{(3)}{\sqrt{3}}$ For 3 phase,  connected generator $E_{PH} = (\text{Line Volts}) = (3)$
(5)	m	<u>PHASES</u> - Number of
(5a)	f	<u>FREQUENCY</u> - In cycles per second
(6)	P	<u>POLES</u> - Number of
(7)	RPM	<u>SPEED</u> - In revolutions per minute
(8)	I_{PH}	<u>PHASE CURRENT</u> - In amperes at rated load
(9)	P.F.	<u>POWER FACTOR</u> - Given in per unit
(9a)	K_c	<u>ADJUSTMENT FACTOR</u> - When P. F. = 0. to .95 set $K_c = 1.$; when P. F. = .95 to 1. set $K_c = 1.05$
(10)	--	<u>LOAD POINTS</u> - The computer program is set up to have the 0.%, 100%, 150%, 200% load points as standard outputs. There is an additional space available on the output sheet for one optional load point. This optional

load point will be the designer's choice and can be selected anywhere in the range of 0 to 200% load. When an optional load calculation is required, insert the per unit load value on the input sheet. The optional load point will be calculated in addition to the standard points listed above. For example, insert .33 on the input sheet when the optional load calculation for 33% load is required in addition to the standard points.

If only the standard points are required, insert 0.0 on the input sheet and the optional load column will be blank.

- | | | |
|-------|-------|--|
| (11) | d | <u>STATOR PUNCHING I.D.</u> - The inside diameter of the stator punching in inches. |
| (11a) | d_r | <u>ROTOR O.D.</u> - The outside diameter of the rotor in inches. |
| (12) | D | <u>PUNCHING O.D.</u> - The outside diameter of the stator punching in inches. |
| (13) | | <u>GROSS STATOR CORE LENGTH</u> - In inches. |
| (14) | n_v | <u>RADIAL DUCTS</u> - Number of. |
| (15) | b_v | <u>RADIAL DUCT WIDTH</u> - In inches. |
| (16) | K_i | <u>STACKING FACTOR</u> - This factor allows for the coating (core plating) on the punchings, the burrs due to slotting, and the deviations in flatness. Approximate values of K_i are given in Table IV. |

THICKNESS OF LAMINATIONS (INCHES)	GAGE	K _i
.014	29	0.92
.018	26	0.93
.025	24	0.95
.028	23	0.97
.063	--	0.98
.125	--	0.99

TABLE IV

(17)

 ℓ_s

SOLID CORE LENGTH - The solid length is the gross length times the stacking factor. If ventilating ducts are used, their length must be subtracted from the gross length also.

$$\ell_s = (K_i) [(\ell) - (n_v) (b_v)] = (16) [(13) - (14) (15)]$$

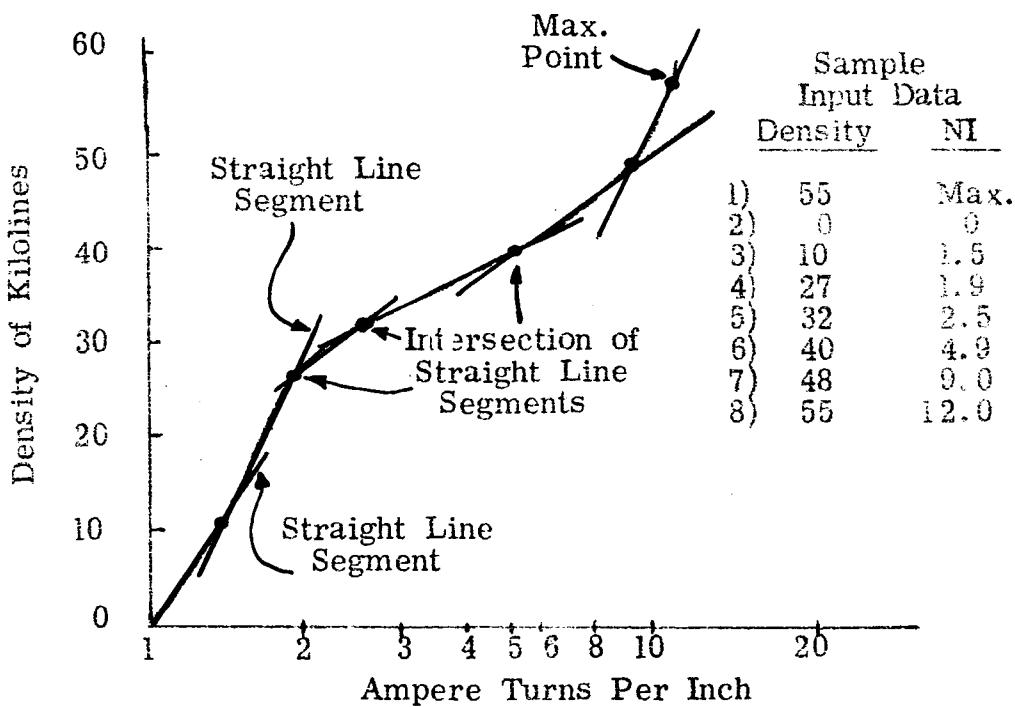
(18)

MATERIAL - This input is used in selecting the proper magnetization curves for stator; tube, south pole and skirt; yoke; north pole, spider and shaft; when different materials are used. Separate spaces are provided on the input sheet for each section mentioned above. Where curves are available on card decks, used the proper identifying code. Where card decks are not available submit data in the following manner:

The magnetization curve must be available on semi-log paper. Typical curves are shown in this manual on Curves 15 and 16. Draw straight line segments through the curve starting with zero density. Record the coordinates of the points where the

straight line segments intersect. Submit these coordinates as input data for the magnetization curve. The maximum density point must be submitted first.

Refer to Figure below for complete sample



- (19) k WATTS/LB - Core loss per lb of stator lamination material.
Must be given at the density specified in (20).
- (20) B DENSITY - This value must correspond to the density used in Item (19) to pick the watts/lb. The density that is usually used is 77.4 kilolines/in².

- (21) 1 TYPE OF STATOR SLOT - Refer to Figure 1, Page
 2 for type of slot.
 3 For (a) slot use 1. as an input
 4 For (b) slot use 2. as an input
 5 For (c) slot use 3. as an input
 6 For (d) slot use 4. as an input
 7 Type 5. is not a slot but instead a particular situation for an open slot where the winding has only
 8 one conductor per slot.
- (22) b₀ ALL SLOT DIMENSIONS - Given in inches per Figure 1,
 b₁ Page . Where the dimension does not apply
 b₂ to the slot being used, insert 0. on input sheet.
 b₃ FOR SLOT TYPE (C)
 b_s $b_s = \frac{(b_1) + (b_3)}{2} = \frac{(22) + (22)}{2}$
 h₀
 h₁
 h₂
 h₃
 h_s
 h_t
 h_w
- (23) Q STATOR SLOTS - Number of.
- (24) h_c DEPTH BELOW SLOTS - The depth of the stator core below
 1 the slots.

Due to mechanical strength reasons, h_C should never be less than 70% of h_S .

$$h_C = \frac{(D) - [(d) + 2(h_S)]}{2} = \frac{(12) - [(11) + 2(22)]}{2}$$

(25) q SLOTS PER POLE PER PHASE

$$q = \frac{(Q)}{(P)(m)} = \frac{(23)}{(6)(5)}$$

(26) T_s STATOR SLOT PITCH

$$T_s = \frac{\pi(d)}{Q} = \frac{\pi(11)}{(23)}$$

(27) $T_{s1/3}$ STATOR SLOT PITCH - 1/3 distance up from narrowest section. For slot (a), (b), (c), and (e)

$$s_{1/3} = \frac{\pi[(d) + .66(h_S)]}{(Q)} = \frac{\pi[(11) + .66(22)]}{(23)}$$

For slot (d)

$$\begin{aligned} & \frac{\pi[(d) + 2(h_0) + 1.32(b_S)]}{(Q)} = \\ & \frac{\pi[(11) + 2(22) + 1.32(22)]}{(23)} \end{aligned}$$

(28) -- TYPE OF WINDING - Record whether the connection is "wye" or "delta". For "wye" conn use 1. for input. For "delta" use 0. for input.

(29) -- TYPE OF COIL - Record whether random wound or formed coils are used. For random wound coils use 0. for input. For formed coils use 1. for input.

- (30) n_s CONDUCTORS PER SLOT - The actual number of conductors per slot. For random wound coils use a space factor of 75% to 80%. Where space factor is the percent of the total slot area that is available for insulated conductors after all other insulation areas have been subtracted out.
- (31) γ THROW - Number of slots spanned. For example, with a coil side in slot 1 and the other coil side in slot 10, the throw is 9.
- (31a) PER UNIT OF POLE PITCH SPANNED - Ratio of the number of slots spanned to the number of slots in a pole pitch. This value must be between 1.0 and 0.5 to satisfy the limits of this program.
- $$= \frac{(\gamma)}{(m)(q)} \quad \frac{(31)}{(5)(25)}$$
- (32) C PARALLEL PATHS, No. of - Number of parallel circuits per phase.
- (33) -- STRAND DIA. OR WIDTH - In inches. For round wire, use strand diameter. For rectangular wire, use strand width. This must be the largest of the two dimensions given for a rectangular wire.
- (34) NST NUMBER OF STRANDS PER CONDUCTOR IN DEPTH - Applies to rectangular wire. In order to have a more flexible conductor and reduce eddy current loss, a stranded conductor is often used. For

example, when the space available for one conductor is .250 width x .250 depth, the actual conductor can be made up of 2 or 3 strands in depth as shown



For a more detailed explanation refer to section titled "Effective Resistance and Eddy Factor" in the Derivations in Appendix.

- | | | |
|-------|-------------|--|
| (34a) | N' ST | <u>NUMBER OF STRANDS PER CONDUCTOR</u> - This number applies to the strands in depth and/or width and is used in calculating the conductor area. Item (34) is different in that it deals with strands in depth only and is used in calculating eddy factors. |
| (35) | d_b | <u>DIAMETER OF BENDER PIN</u> - in inches - This pin is used in forming coils. Use .25 inch for stator O.D. < 8 inches use .50 inches for stator O.D. ≥ 8 inches. |
| (36) | ℓ_{e2} | <u>COIL EXTENSION BEYOND CORE</u> in Inches - Straight portion of coil that extends beyond stator core. |
| (37) | h_{ST} | <u>HEIGHT OF UNINSULATED STRAND</u> in Inches - This value is the vertical height of the strand and is used in eddy factor calculations. Set this value = 0 for round wire. |
| (38) | h' ST | <u>DISTANCE BETWEEN CENTERLINES OF STRANDS IN DEPTH</u> in inches. |

- (39) -- STATOR COIL STRAND THICKNESS in inches - For rectangular conductors only. For round wire insert 0. on input sheet. This must be the narrowest dimension of the two dimensions given for a rectangular wire.
- (40) τ_{SK} SKEW - Stator slot skew in inches at stator I.D.
- (41) τ_P POLE PITCH in inches.

$$\tau_P = \frac{\pi(d)}{(P)} = \frac{\pi(11)}{(6)}$$
- (42) K_{SK} SKEW FACTOR - The skew factor is the ratio of the voltage induced in the coils to the voltage that would be induced if there were no skew.
When $\tau_{SK} = 0$, $K_{SK} = 1$

$$K_{SK} = \frac{\sin \left[\frac{\pi(\tau_{SK})}{2(\tau_P)} \right]}{\frac{\pi(\tau_{SK})}{2(\tau_P)}} = \frac{\sin \left[\frac{\pi(40)}{2(41)} \right]}{\frac{\pi(40)}{2(41)}}$$
- (42a) PHASE BELT ANGLE - Input
For phase belt angle = 60° insert 60 on input sheet.
For phase belt angle = 120° insert 120 on input sheet.
- (43) K_d DISTRIBUTION FACTOR - The distribution factor is the ratio of the voltage induced in the coils to the voltage that would be induced if the windings

were concentrated in a single slot. See Table 2 for compilation of distribution factors for the various harmonics.

For 60° phase belt angle and $q = \text{integer}$ when
 $(42a) = 60$ and $(25) = \text{integer}$.

$$K_d = \frac{\sin 30^\circ}{(q) \sin [30/(q)]} = \frac{\sin 30^\circ}{(25) \sin [30/(25)]}$$

For 60° phase belt angle and $(q) \neq \text{integer} = N/B$ reduced to lowest terms.

When $(43a) = 1$ and $(25) \neq \text{integer} = N/B$ reduced to lowest terms

$$K_d = \frac{\sin 30^\circ}{(N) \sin [30/(N)]} = \frac{\sin 30^\circ}{(43) \sin [30/(43)]}$$

For 120° phase belt angle and $(q) = \text{integer}$

When $(43a) = 120$ and $(25) = \text{integer}$

$$K_d = \frac{\sin 60^\circ}{2(q) \sin [30/(q)]} = \frac{\sin 60^\circ}{2(25) \sin [30/(25)]}$$

For 120° phase belt angle and $q \neq \text{integer}$

When $(43a) = 120$ and $(25) \neq \text{integer} = N/B$ reduced to lowest terms

$$K_d = \frac{\sin 60^\circ}{2(N) \sin [30/(N)]} = \frac{\sin 60^\circ}{2(43) \sin [30/(43)]}$$

(44) K_P PITCH FACTOR - The ratio of the voltage induced in the coil to the voltage that would be induced in a full pitched coil. See Table 1 for compilation of the pitch factors for the various harmonics.

$$K_P = \sin \left[\frac{(Y)}{(m)(q)} \times 90^\circ \right] = \sin \left[\frac{(31)}{(5)(25)} \times 90^\circ \right]$$

(45) n_e TOTAL EFFECTIVE CONDUCTORS - The actual number of effective series conductors in the stator winding taking into account the pitch and skew factors but not allowing for the distribution factor.

$$n_e = \frac{(Q)(n_s)(K_P)(K_{SK})}{(C)} = \frac{(23)(30)(44)(42)}{(32)}$$

(46) a_c CONDUCTOR AREA OF STATOR WINDING in (inches)² - The actual area of the conductor taking into account the corner radius on square and rectangular wire. See the following table for typical values of corner radii

$$\text{If } (39) = 0 \text{ then } a_c = .25\pi(\text{Dia})^2 = .25\pi(33)^2$$

$$\text{If } (39) \neq 0 \text{ then } a_c = (N' ST) \left[(\text{strand width})(\text{strand depth}) - (.858 r_c^2) \right] = (34a) \left[(33)(39) - (.858 r_c^2) \right]$$

where $.858 r_c^2$ is obtained from Table V below.

<u>(39)</u>	<u>(33) .188</u>	<u>.189 (33) .75</u>	<u>(33) .751</u>
.050	.000124	.000124	.000124
.072	.000210	.000124	.000124
.125	.000210	.00084	.000124
.165	.000840	.00084	.003350
.225	.001890	.00189	.003350
.438	--	.00335	.007540
.688	--	.00754	.01340
--	--	.03020	.03020

TABLE V

(47)	s_s	<u>CURRENT DENSITY</u> - Amperes per square inch of stator conductor
		$s_s = \frac{(I_{PH})}{(C)(a_c)} = \frac{(8)}{(32)(46)}$
(48)	L_E	<u>END EXTENSION LENGTH</u> in inches - Can be an input or output. For L_E to be output, insert 0. on input sheet. For L_E to be input, calculate per following: When (29) = 0. then:
		$L_E = .5 + \frac{K_T \pi (Y) [(d) + (h_s)]}{Q} = .5 + \begin{cases} 1.3 & \text{If } (6) = 2 \\ 1.5 & \text{If } (6) = 4 \\ 1.7 & \text{If } (6) = 4 \end{cases} \pi (31) [(11) + (22)] \quad (23)$
		When (29) = 1. then: $\begin{aligned} L_E &\approx 2 \ell_{e2} + \pi \left[\frac{h_1}{2} + \text{dia} \right] + Y \left[\frac{\tau_s^2}{\sqrt{\tau_s^2 - b_s^2}} \right] \\ &= 2 (36) + \pi \left[\frac{(22)}{2} + (35) \right] + (31) \left[\frac{(26)^2}{\sqrt{(26)^2 - (22)^2}} \right] \end{aligned}$
(49)	ℓ_t	<u>1/2 MEAN TURN</u> - The average length of one conductor in inches. $\ell_t = (\ell) + (L_E) = (13) + (44)$
(50)	$x_s^o C$	<u>STATOR TEMP °C</u> - Input temp at which F.L. losses will be calculated. No load losses and cold resistance will be calculated at 20°C.

(51) ρ_s

RESISTIVITY OF STATOR WINDING - In micro ohm-inches @ 20°C. If tables are available using units other than that given above, use Table VI for conversion to ohm-inches.

ρ	ohm-cm	ohm-in	ohm-cir mil/ft
1 ohm-cm =	1.000	0.3937	6.015×10^6
1 ohm-in =	2.540	1.000	1.528×10^7
1 ohm-cir mil/ft =	1.662×10^{-7}	6.545×10^{-8}	1.000

TABLE VI
Conversion Factors for Electrical Resistivity

(52) ρ_s
(hot)

RESISTIVITY OF STATOR WINDING - Hot at X_s °C in micro ohm-inches

$$\rho_{s(\text{hot})} = (\rho_s) \left[\frac{(X_s \text{ } ^\circ\text{C}) + 234.5}{254.5} \right] = (51) \left[\frac{(50) + 234.5}{254.5} \right]$$

(53) R_{SPH}
(cold)

STATOR RESISTANCE/PHASE - Cold @ 20°C in ohms

$$R_{SPH(\text{cold})} = \frac{(\rho_s)(n_s)(Q)(l_t)}{(m)(a_c)(C)^2} \times 10^{-6} = \frac{(51)(30)(23)(49)}{(5)(46)(32)^2} \times 10^{-6}$$

(54) R_{SPH}
(hot)

STATOR RESISTANCE/PHASE - Calculated @ X °C in ohms.

$$R_{SPH(\text{hot})} = \frac{(\rho_s \text{ hot})(n_s)(Q)(l_t)}{(m)(a_c)(C)^2} \times 10^{-6} \frac{(52)(30)(23)(49)}{(5)(46)(32)^2} \times 10^{-6}$$

(55) EF
(top)

EDDY FACTOR TOP - The eddy factor of the top coil. Calculate this value at the expected operating temperature of the machine. For round wire

$$EF_{\text{top}} = 1$$

$$EF_{top} = 1 + \left\{ .584 + \left[\frac{N_{st}^2 - 1}{16} \right] \left[\frac{h'_{st} l}{h_{st} l_t} \right]^2 \right\} 3.35 \times 10^{-3}$$

$$\left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_{shot})} \right]^2$$

$$= 1 + \left\{ .584 + \left[\frac{(34)^2 - 1}{16} \right] \left[\frac{(38)(13)}{(37)(49)} \right]^2 \right\} 3.35 \times 10^{-3}$$

$$\left[\frac{(37)(30)(5a)(46)}{(22)(52)} \right]^2$$

(56)

EF
(bot)

EDDY FACTOR BOTTOM - The eddy factor of the bottom coil at the expected operating temperature of the machine. For round wire $EF_{(bot)} = 1$

$$EF_{(bot)} = (EF_{(top)}) - 1.677 \left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_{shot})} \right]^2 \times 10^{-3}$$

$$= (55) - 1.677 \left[\frac{(37)(30)(5a)(46)}{(22)(52)} \right] 10^{-3}$$

(57)

btm

STATOR TOOTH WIDTH 1/2 way down tooth in inches -
For slots type (a), (b), (d) and (e), Figure I

$$b_{tm} = \frac{\pi \overline{(d)} + (h_s)}{(Q)} - (b_s) = \frac{\pi \overline{(11) + (22)}}{(23)} - (22)$$

FOR SLOT TYPE (c), Figure 1

$$b_{tm} = \frac{\pi \overline{(d) + 2(h_s)}}{Q} - (b_3) = \frac{\pi \overline{(11) + 2(22)}}{(23)} - (22)$$

(57a) $b_t \frac{1}{3}$

STATOR TOOTH WIDTH 1/3 distance up from narrowest section
 For slots type (a), (b) and (e)

$$b_t \frac{1}{3} = (\tau_s \frac{1}{3}) - (b_s) = (27) - (22)$$

For slot type (c)

$$b_t \frac{1}{3} = b_{tm} = (57)$$

For slot type (d)

$$b_t \frac{1}{3} = (\tau_{1/3}) - \frac{2\sqrt{2}}{3} (b_s) = (27) - .94(22)$$

(58) b_t

TOOTH WIDTH AT STATOR I.D. in inches -

For partially closed slot

$$b_t = \frac{\pi(d)}{(Q)} - b_0 = \frac{\pi(11)}{(23)} - (22)$$

For open slot

$$b_t = \frac{\pi(d)}{(Q)} - b_s = \frac{\pi(11)}{(23)} - (22)$$

(59) g

MAIN AIR GAP in inches

(59a) g_2

AUXILIARY GAP, INNER - in inches

(59b) g_3

AUXILIARY GAP, OUTER - in inches

(60) C_X

REDUCTION FACTOR - Used in calculating conductor permeance

and is dependent on the pitch and distribution factor.

This factor can be obtained from Graph 1 with an assumed K_d of .955 or calculated as shown

$$C_X = \frac{(K_X)}{(K_P)^2 (K_d)^2} = \frac{(61)}{(44)^2 (43)^2}$$

(61) K_X

FACTOR TO ACCOUNT FOR DIFFERENCE in phase current
in coil sides in same slot.

For 60° phase belt winding, i.e. when (42a) = 60

$$K_X = \frac{1}{4} \left[\frac{3(y)}{(m)(q)} + 1 \right] \text{ where } \frac{2}{3} \leq \frac{(y)}{(m)(q)} \leq 1.0$$

$$K_X = \frac{1}{4} \left[\frac{3(31)}{(5)(25)} + 1 \right] \text{ where } \frac{2}{3} \leq \frac{(3la)}{(5)(25)} \leq 1.0$$

or

$$K_X = \frac{1}{4} \left[\frac{6(y)}{(m)(q)} - 1 \right] \text{ where } \frac{1}{2} \leq \frac{(3la)}{(m)(q)} \leq \frac{2}{3}$$

$$K_X = \frac{1}{4} \left[\frac{6(31)}{(5)(25)} - 1 \right] \text{ where } \frac{1}{2} \leq \frac{(3la)}{(5)(25)} \leq \frac{2}{3}$$

For 120° phase belt winding, i.e. when (42a) = 120

$$K_X = .75 \text{ when } \frac{2}{3} \leq \frac{(y)}{(m)(q)}$$

$$K_X = .75 \text{ when } \frac{2}{3} \leq \frac{(3la)}{(m)(q)}$$

or

$$K_X = .05 \left[\frac{24(y)}{(m)(q)} - 1 \right] \text{ where } \frac{1}{2} \leq \frac{(y)}{(m)(q)} \leq \frac{2}{3}$$

$$K_X = .05 \left[\frac{24(31)}{(3)(25)} - 1 \right] \text{ where } \frac{1}{2} \leq \frac{(3la)}{(3)(25)} \leq \frac{2}{3}$$

(62) λ_i

CONDUCTOR PERMEANCE - The specific permeance for the portion of the stator current that is embedded in the iron. This permeance depends upon the configuration of the slot.

(a) For open slots

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(T_s)(g)} + \frac{.35(b_t)}{(T_s)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)} \right]$$

(b) For partially closed slots with constant slot width

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_o)}{(b_o)} + \frac{2(h_t)}{(b_o) + (b_s)} + \frac{(h_w)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{2(22)}{(22) + (22)} + \frac{(22)}{(22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)} \right]$$

(c) For partially closed slots (tapered sides)

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_o)}{(b_o)} + \frac{2(h_t)}{(b_o) + (b_1)} + \frac{2(h_w)}{(b_1) + (b_2)} + \frac{(h_1)}{3(b_2)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{2(22)}{(22) + (22)} + \frac{2(22)}{(22) + (22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)} \right]$$

(d) For round slots

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[.62 + \frac{(h_o)}{(b_o)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[.62 + \frac{(22)}{(22)} \right]$$

(e) For open slots with a winding of one conductor per slot

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + .6 + \frac{(g)}{2(\tau_s)} + \frac{(\tau_s)}{4(g)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{(22)}{3(22)} + .6 + \frac{(59)}{2(26)} + \frac{(26)}{4(59)} \right]$$

(63) K_E LEAKAGE REACTIVE FACTOR for end turn

$$K_E = \frac{\text{Calculated value } (L_E)}{\text{Value } (L_E) \text{ from Graph 1}} \quad (\text{For machines where } (11) > 8'')$$

where $L_E = (48)$ and abscisa of Graph 1 = $(Y)(T_s) = (31)(26)$

$$K_E = \sqrt{\frac{\text{Calculated value of } (L_E)}{\text{Value } (L_E) \text{ from Graph 1}}} \quad (\text{For machines where } (11) < 8'')$$

(64) λ_E END WINDING PERMEANCE - The specific permeance for the end extension portion of the stator winding

$$\gamma_E = \frac{6.28(K_E)}{(\ell)(K_d)^2} \left[\frac{\phi_E L_E}{2n} \right] = \frac{6.28(63)}{(13)(43)^2} \left[\frac{Q_E L_E}{2n} \right]$$

The term $\left[\frac{\phi_E L_E}{2n} \right]$ is obtained from Graph 1.

The symbols used in this (term) do not apply to those of this design manual. Reference information for the symbol origin is included on Graph 1.

(65) --

WEIGHT OF COPPER - The weight of stator copper in lbs.

$$\#s \text{ copper} = .321(n_s)(Q)(a_c)(\ell_t) = .321(30)(23)(46)(49)$$

NOTE: This answer is given in lbs. based on the density of copper. If any other material is used, the answer on output sheet can be converted by the designer by multiplying by the ratio of densities.

(66)

WEIGHT OF STATOR IRON - in lbs.

$$\text{#}'s \text{ iron} = .283 \left\{ (b_{tm})(Q)(\ell_s)(h_s) + \pi \left[(D) - (h_c) \right] (h_c)(\ell_s) \right\}$$

$$.283 \left\{ (57)(23)(17)(22) + \pi \left[(12) - (24) \right] (24)(17) \right\}$$

(67)

 K_s CARTER COEFFICIENT

$$K_s = \frac{(\tau_s) [5(g) + (b_s)]}{(\tau_s) [5(g) + (b_s)] - (b_s)^2} \quad (\text{For open slots})$$

$$K_s = \frac{(26) [5(59) + (22)]}{(26) [5(59) + (22)] - (22)^2}$$

$$K_s = \frac{\tau_s [4.44(g) + .75(b_o)]}{\tau_s [4.44(g) + .75(b_o)] - (b_o)^2} \quad (\text{For partially closed slots})$$

$$K_s = \frac{(26) [4.44(59) + .75(22)]}{(26) [4.44(59) + .75(22)] - (22)^2}$$

(68)

--

MAIN AIR GAP AREA - The area of the gap surface at the stator bore.

$$\text{Gap Area} = \pi(d)(\ell) = \pi(l) \quad (13)$$

(69)

 g_e EFFECTIVE AIR GAP

$$g_e = (K_s)(g) = (67)(59)$$

(70)

 A_{g2} AREA OF AUXILIARY AIR GAP

$$A_{g2} = \frac{\pi}{4} (d_{g2})^2 = \frac{\pi}{4} (87)^2$$

(70a)	A _{g3}	<u>AREA OF OUTER AUXILIARY AIR GAP</u> $A_{g3} = \pi(d_{g3})(l_{g3}) = (87)(87)$
(71)	C ₁	<u>THE RATIO OF MAXIMUM FUNDAMENTAL</u> of the field form to the actual maximum of the field form - This term can be an input or output. For C ₁ to be output insert 0. on input sheet. For C ₁ to be input, determine C ₁ as follows: For pole heads with only one radius, C ₁ is obtained from curve #4. The abscisa is "pole embrace" (α) = (77). The graphical flux plotting method of determining C ₁ is explained in the section titled "Derivations" in the Appendix.
(72)	C _W	<u>WINDING CONSTANT</u> - The ratio of the RMS line voltage for a full pitched winding to that which would be introduced in all the conductors in series if the density were uniform and equal to the maximum value. This value can be an input or output. For C _W to be an output, insert 0. on input sheet. For C _W to be an input, calculate as follows: $C_W = \frac{(E)(C_1)(K_d)}{\sqrt{2}(E_{PH})(m)} = \frac{(3)(71)(43)}{\sqrt{2}(4)(5)}$ Assuming K _d = .955, then C _W = .225 C ₁ for three phase delta machines and C _W = .390 C ₁ for three phase star machines.

(73) C_p

POLE CONSTANT - The ratio of the average to the maximum value of the field form. This ratio can be an input or output. For C_p to be an output, insert 0. on input sheet. For C_p to be an input, determine as follows:

For pole heads with more than one radius C_p is calculated from the same field form that was used to determine C_1 , and this method is described in the section titled "Derivations" in the Appendix. For pole heads with only one radius C_p is obtained from curve #4. Note the correction factor at the top of the curve.

(74) C_M

DEMAGNETIZING FACTOR - direct axis - This factor can be an input or output. For C_M to be an output, insert 0. on input sheet. For C_M to be an input, determine as follows:

$$C_M = \frac{(\alpha)\pi + \sin[(\alpha)\pi]}{4 \sin[(\alpha)\pi/2]} = \frac{(77)\pi + \sin[(77)\pi]}{4 \sin[(77)\pi/2]}$$

C_M can also be obtained from curve 9.

(75) C_q

CROSS MAGNETIZING FACTOR - quadrature axis - This factor can be an input or output. For C_q to be an output, insert 0. on input sheet. For C_q to be an input, determine as follows:

$$C_q = \frac{\frac{1}{2} \cos[(\alpha) \pi/2] + (\alpha)\pi - \sin[(\alpha)\pi]}{4 \sin[(\alpha) \pi/2]}$$

$$= \frac{\frac{1}{2} \cos[(77) \pi/2] + (77)\pi - \sin[(77)\pi]}{4 \sin[(77) \pi/2]}$$

} VALID FOR
CONCENTRIC
POLES.

C_q can also be obtained from curve 9.

(76)

POLE DIMENSION LOCATIONS

b_{p2} - width of pole at edge of stator stack (wide end).

b_{p1} - width of pole at end (narrow end).

t_{p2} - thickness of pole at edge of stator stack.

t_{p1} - thickness of pole at end.

ℓ_{co} - length of coil.

ℓ_p - length of pole.

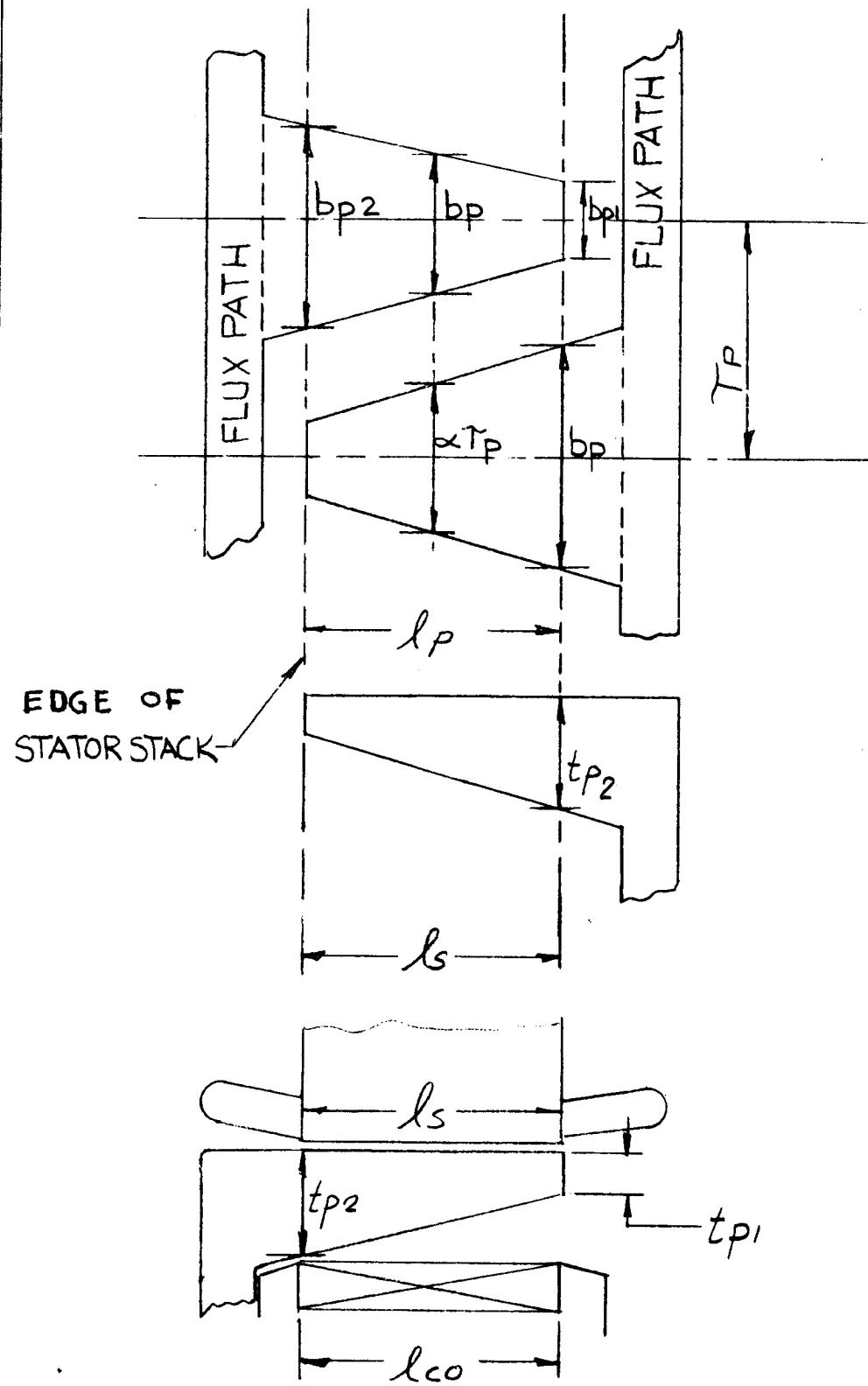


FIG 2

(77)

 \propto POLE EMBRACE

$$\propto = \frac{(b_{p1}) + (b_{p2})}{2 (T_p)} = \frac{(76) + (76)}{2 (41)}$$

(77a)

The next **11** items deal with the calculation of rotor and stator leakage permeance. A number of illustrations are included to help identify and locate the actual path. This computer program is set up to handle the permeance calculations two ways.

- 1) P_1 through P_7 can be calculated by the computer.
For this case, insert 0.0 on the input sheet.
- 2) P_1 through P_7 can be calculated by the designer.
For this case, insert the actual calculated value on the input sheet.

Permeance calculations P_1 through P_7 are all based on the equations

$$P = \frac{u \text{ (area)}}{\ell}$$

Where $u = 3.19$

Area = cross-sectional area perpendicular to
= length of permeance leakage path

Many of the equations used in this section are taken from Roter's "Electromagnetic Devices". Refer to the supplement at the end of this computer design manual for an explanation of each condition.

(78)

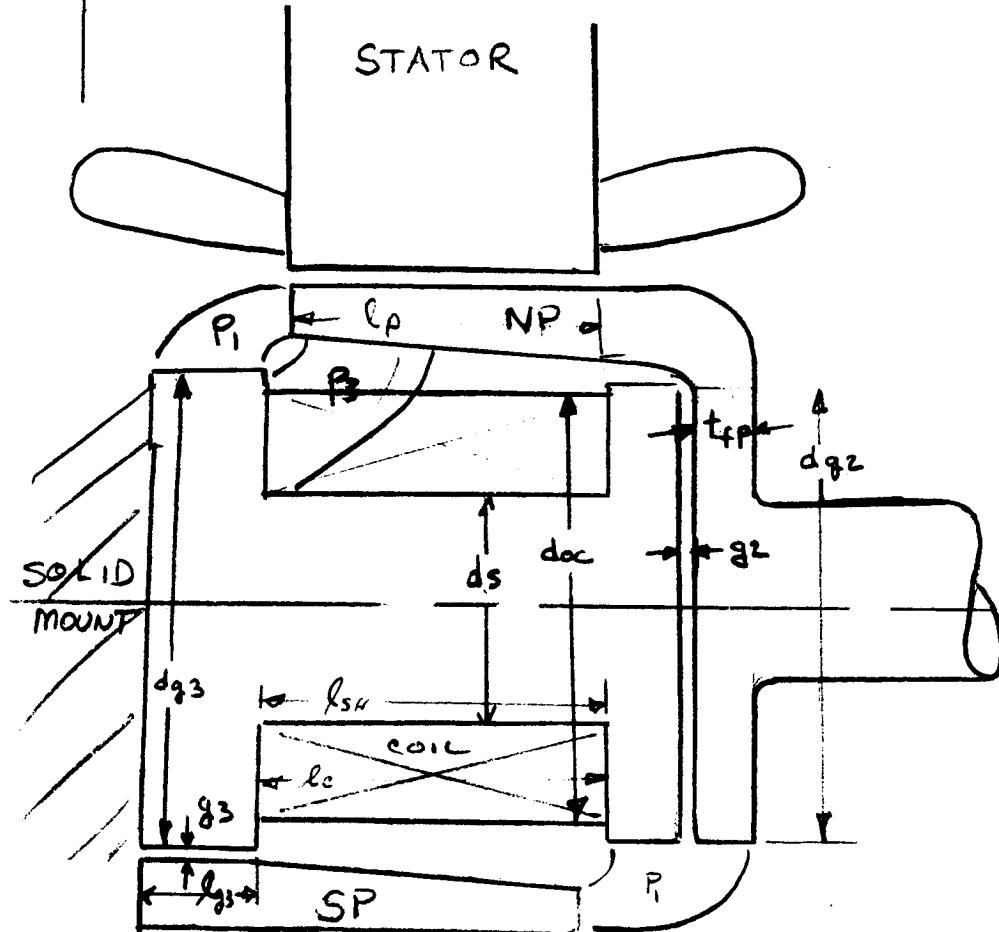
ROTOR AND STATOR DIMENSIONS l_{g3} - axial length of air gap (g3) d_{g3} - diameter at air gap (g3) d_{g2} - diameter of the circle containing flux in gap (g2) d_s - diameter of shaft (equal to coil inside diameter) l_{SH} - length of shaft (flux carrying portion) t_{fp} - thickness of flux plate d_{oc} - outside diameter of coil l_{co} - length of coil (axial length)

FIG 3

- (79) a_p POLE AREA - The effective cross sectional area of the pole.
 $A_p = (b_{p2}) (t_{p2}) = (76) (76)$
- (80) P_1 POLE HEAD END LEAKAGE - This input can be either 0.0
or the actual value if available. Refer to item 86
for explanation. See Figure 4,5 for location.
- $$P_1 = \frac{3.19 (b_{p1}) (t_{p1})}{\ell_1} = \frac{3.19 (76) (76)}{(80a)}$$
- (80a) ℓ_1 LENGTH OF PERMEANCE PATH P_1 - ℓ_1 is the length of
permeance path P_1 and must be obtained from design
layout. Note this value (ℓ_1) must appear as a
input when $P_1 = 0.0$
- (81) P_2 POLE HEAD SIDE LEAKAGE - This input can be either 0.0
or the actual value if available. Refer to item 86
for explanation. See Figure 4 for location.
- $$P_2 = 3.19 \left[\frac{(t_{p1}) + (t_{p2})}{2} \right] \frac{(\ell_p)}{(\ell_2)}$$
- $$= 3.19 \left[\frac{(76) + (76)}{2} \right] \frac{(87)}{(81a)}$$
- (81a) ℓ_2 LENGTH OF PERMEANCE PATH P_2 - ℓ_2 is the length of
permeance path P_2 and must be obtained from design
layout. Note: This value (ℓ_2) must appear as an
input when $P_2 = 0.0$

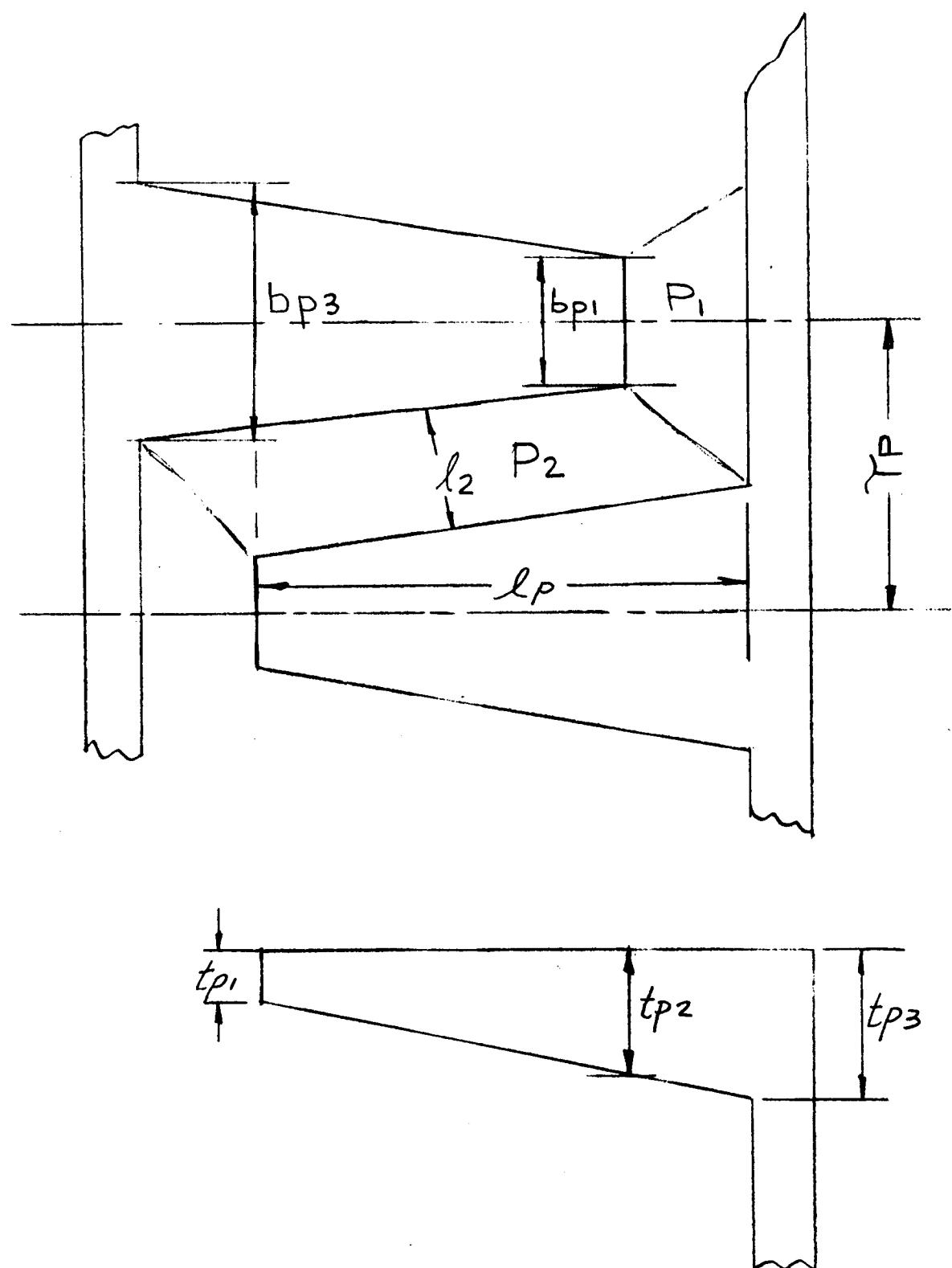


FIG 4.

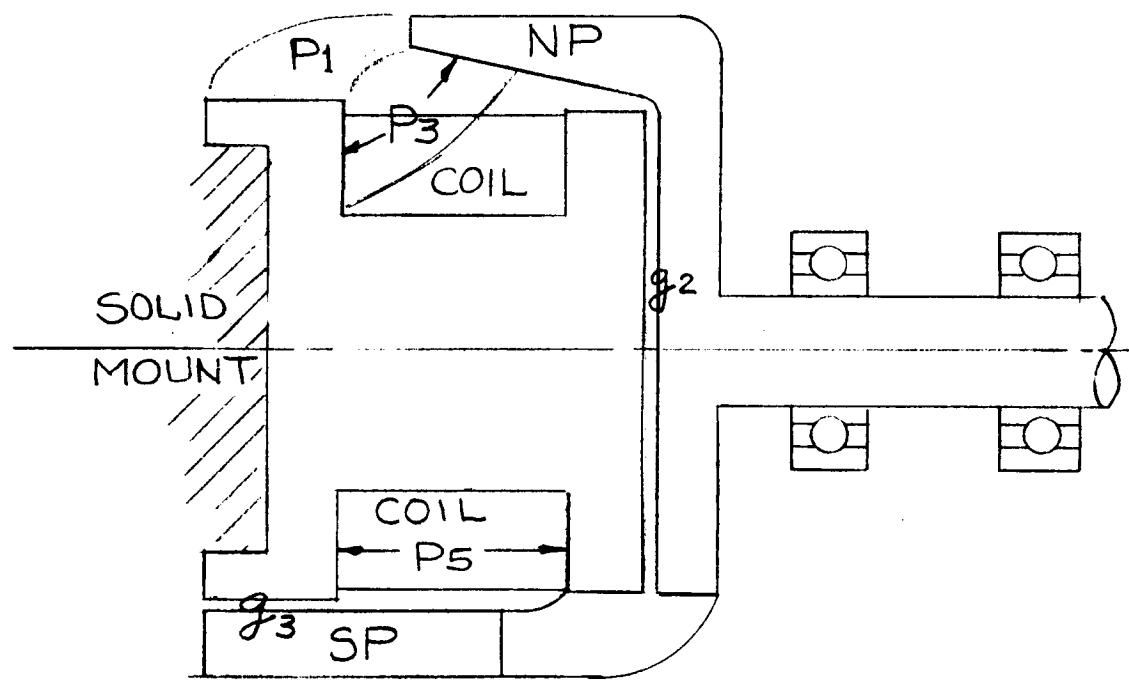


FIG. 5

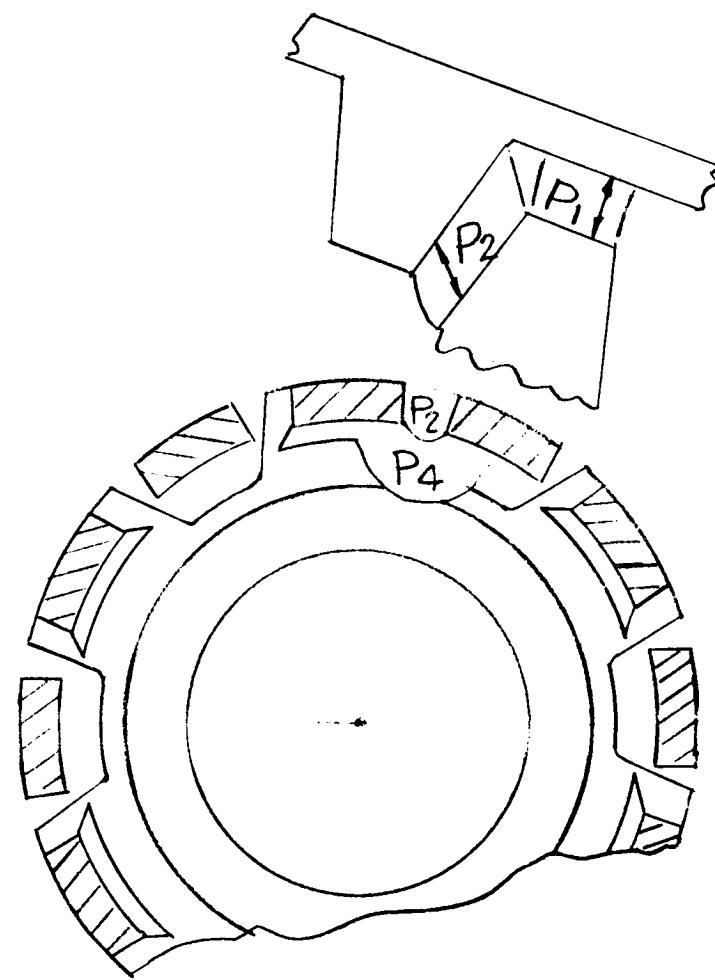


FIG 6

(82) P₃POLE UNDERSIDE TO FLUX PLATE LEAKAGE PERMEANCE -

This input can be either 0.0 or the actual value if available. Refer to item 86 for explanation. See Figure 5 for location.

$$P_3 = 3.19 \left[\frac{3(b_{p1}) + (b_{p2})}{8} \right] (\ell_p) \frac{(82a)}{\ell_3}$$

$$= 3.19 \left[\frac{3(76) + (76)}{8} \right] \frac{(78)}{(82a)}$$

(82a) ℓ_3

LENGTH OF PERMEANCE PATH P₃ - ℓ_3 is the length of permeance path P₃ and must be obtained from design layout. Note: This value (ℓ_3) must appear as an input when P₂ = 0.0

(83) P₄POLE UNDERSIDE TO POLE UNDERSIDE LEAKAGE PERMEANCE

This input can be either 0.0 or the actual value if available. Refer to item 77a for explanation. See Figure 6 for location.

For 6 poles or more i.e. when (6) ≥ 6 calculate as follows:

$$*P_4 = \frac{3.19 (\ell_p) \ln \left[1 + \frac{(b_{p1}) + (b_{p2})}{(Z)} \right]}{\pi}$$

$$= \frac{3.19 (76) \ln \left[1 + \frac{(76) + (76)}{(83)} \right]}{\pi}$$

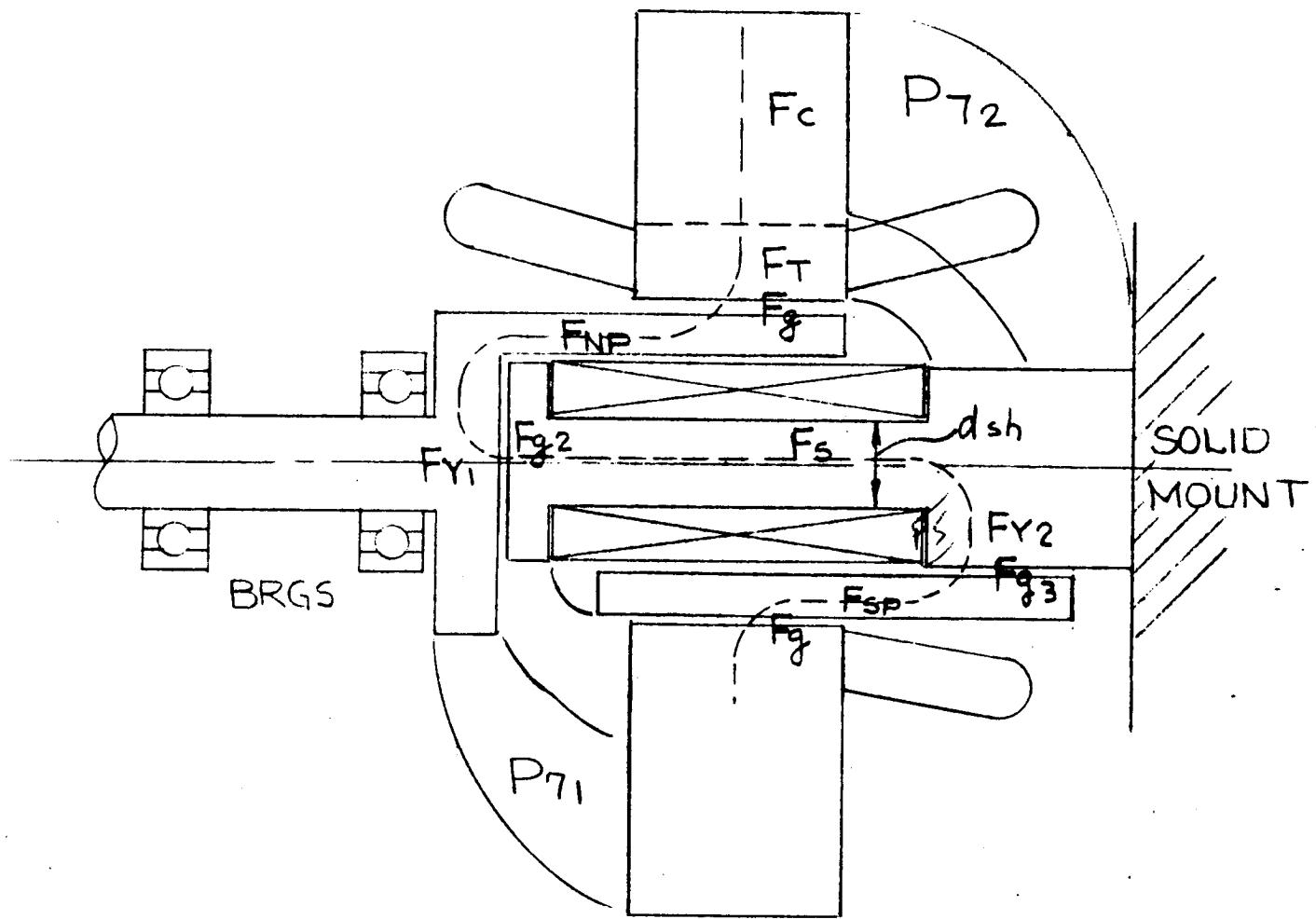


FIG 7

$$\text{where } Z = \gamma_p - \left[\frac{(b_{p1}) + (b_{p2})}{2} \right] = (41) - \frac{(76) + (76)}{2}$$

For 4 poles i.e. when (6) = 4 calculate as follows:

$$\begin{aligned} *P_4 &= \frac{3.19(\ell_p)}{2} \ln \left[1 + \frac{(b_{p1} + b_{p2})}{Z} \right] \\ &= \frac{3.19(76)}{\pi} \frac{3}{2} \ln \left[1 + \frac{(76) + (76)}{83} \right] \end{aligned}$$

* The formula for P_4 is taken from the supplemental at the end of this computer design manual.

- (84) P₅ FIELD COIL LEAKAGE PERMEANCE - This input can be either 0.0 or the actual value if available. Refer to item 77a for explanation. See Figure 7 for location.

$$\begin{aligned} P_5 &= \frac{3.19}{(\ell_{co})} \frac{\pi}{4} \left[\frac{(d_{oc})^2}{4} - \frac{(d_s)^2}{4} \right] \\ &= \frac{3.19}{(78)} \frac{\pi}{4} \left[\frac{(78)^2}{4} - \frac{(78)^2}{4} \right] \end{aligned}$$

- (86) P₇ STATOR TO ROTOR LEAKAGE PERMEANCE - This input can be either 0.0 or the actual value if available. Refer to item 86 for explanation. See Figure 7 for location.

$$\begin{aligned}
 P_7 &= 3.19 \frac{\pi}{2} \left[\frac{(d_r) + (D)}{2} \right] \left[\frac{(D) - (d_r)}{2} \right] + \pi(d_g 2)(l_g 3) \\
 &\quad \hline l_7 \\
 &= 3.19 \frac{\pi}{2} \left[\frac{(11a) - (12)}{2} \right] \left[\frac{(12) - (11a)}{2} \right] + \pi(78)(78) \\
 &\quad \hline (86)
 \end{aligned}$$

where $l_7 = \frac{(D) - (d_r)}{2} - \frac{(12) - (11a)}{2}$

- (37) The next set of calculations deals with the no load saturation. No equation as set up in this section can be used to calculate the complete no load saturation for any voltage. When the no load saturation data is required at various voltages, insert 1. on the input sheet for "No Load Sat". The computer will then calculate the complete no load saturation curve at 80, 90, 100, 110, 120, 130, 140, 150, and 160% of rated volts. When the complete saturation data is not necessary, insert 0. on the input sheet and the computer will calculate to 100% volt data.

(88)	ϕ_T	<u>TOTAL FLUX IN KILO LINES</u>
		$\phi_T = \frac{6(E)10^6}{(C_W)(n_e)(RPM)} = \frac{6(3)10^6}{(72)(45)(17)}$
(91)	B_t	<u>TOOTH DENSITY</u> in Kilo Lines/in ² - The flux density in the stator tooth at 1/3 of the distance from the minimum section.
		$B_t = \frac{\phi_T}{(Q)(l_s)(b_t 1/3)} = \frac{(88)}{(23)(17)(57a)}$
(92)	ϕ_p	<u>FLUX PER POLE</u> in Kilo Lines
		$\phi_p = \frac{(\phi_T)(C_p)}{(P)} = \frac{(88)(73)}{(6)}$
(94)	B_c	<u>CORE DENSITY</u> in Kilo Lines/in ² - The flux density in the stator core
		$B_c = \frac{(\phi_p)}{2(h_c)(l_s)} = \frac{(92)}{2(24)(17)}$
(95)	B_g	<u>GAP DENSITY</u> in Kilo Lines/in ² - The maximum flux density in the air gap
		$B_g = \frac{(\phi_T)}{\pi(d)(l)} = \frac{(88)}{(11)(13)}$
(96)	F_g	<u>AIR GAP AMPERE TURNS</u> - The field ampere turns per pole required to force flux across the air gap when operating at no load with rated voltage.
		$F_g = \frac{(B_g)(g_e)}{3.19} = \frac{(95)(69)}{3.19}$

(97)

 F_T STATOR TOOTH AMPERE TURNS

$$F_T = h_s \left[NI/in \text{ at density } (B_t) \right]$$

= (22) $\left[\begin{array}{l} \text{Look up on stator magnetization curve given} \\ \text{in (18) @ density (91)} \end{array} \right]$

(98)

 F_C STATOR CORE AMPERE TURNS

$$F_C = \left[\frac{\pi[(D) - (h_c)]}{4(P)} \right] \left[NI/in @ \text{density of } (B_c) \right]$$

$$= \left[\frac{\pi[(12) - (24)]}{4(6)} \right] \left[\begin{array}{l} \text{Look up on stator magnetization} \\ \text{curve given in (18) @ density (94)} \end{array} \right]$$

(98a)

 F_s STATOR AMPERE TURNS, total

$$F_s = (F_T) + (F_C) = (97) + (98)$$

(99)

 ϕ_7 STATOR TO SHAFT AND FLUX PLATE LEAKAGE FLUX -

The leakage flux from the stator to the yoke and rotor, all of which crosses the auxiliary air gaps (g_2) and (g_3)

$$\begin{aligned} \phi_7 &= \left[(F_P) + (F_g) + (F_T) + (F_C) + \frac{(F_{g2}) + (F_{g3})}{2} \right] (P_7) \times 10^{-3} \\ &= \left[(104) + (96) + (97) + (98) + \frac{(123) + (120)}{2} \right] (86) \times 10^{-3} \end{aligned}$$

The items to follow

are to be

calculated for variable loads. The first set

of calculations are at no load. These calculations will then be repeated for 100% load. From then on any variation in load would be a repeat of the 100% load calculations with the proper percent load inserted.

(100) ϕ_l

ROTOR LEAKAGE FLUX - at no load

$$\begin{aligned}\phi_l &= \left[2(F_g) + 2(F_s) \right] \left[(P_1) + (P_2) + (P_3) + (P_4) \right] X10 \\ &= \left[2(96) + 2(98a) \right] \left[(80) + (81) + (82) + (83) \right] X10\end{aligned}$$

(102) ϕ_{PT}

TOTAL FLUX PER POLE - at no load

$$\phi_{PT} = \phi_p + \frac{\phi_l}{P} = (92) + \frac{(100)}{(6)}$$

(103) B_p

POLE DENSITY - The apparent flux density at the base of the pole. Note that no provision is made in this manual for calculating the density in the spider section. It is, therefore, important to remember not to restrict the flux area through this section.

$$B_p = \frac{(\phi_{PT})}{(a_p)} = \frac{(102)}{(79)}$$

(104) F_P

POLE AMPERE TURNS - at no load. The ampere turns per pole required to force the flux through the pole at no load rated voltage. The no load pole ampere turns per pole are calculated as the product of (I_p) times the NI per inch at the density (B_P). Use magnetization curve submitted per Item (18) for rotor.

$$F_P = (I_p) \left[NI/in @ \text{density } (B_P) \right]$$

$$= (76) \left[\begin{array}{l} \text{Look up on rotor magnetization curve} \\ \text{given in (18) @ density (103)} \end{array} \right]$$

(108) ϕ_{g2}

FLUX CROSSING THE AUXILIARY AIR GAP - Kilolines

$$\phi_{g2} = (\phi_{PT}) \frac{(P)}{2} + \frac{(\phi_7)}{2}$$

$$= (102) \frac{(6)}{2} + \frac{(99)}{2}$$

(111) ϕ_{SH}

FLUX IN SHAFT

$$\phi_{SH} = (\phi_{g2}) + (\phi_5) = (108) + (118)$$

(112) A_S

AREA OF SHAFT in inches² - cross-sectional to flux

$$\text{Where } A_S = \frac{\pi}{4} (d_S)^2 = \frac{\pi}{4} (78)^2$$

(113)

 B_{sh} FLUX DENSITY IN SHAFT

$$B_s = \frac{\Phi_{sh}}{(A_s)} = \frac{(111)}{(112)}$$

(114)

 F_{sh} AMPERE TURN DROP IN SHAFT

$$F_{sh} = [\bar{l}_{sh}] \left[\text{NI/inch at density } (B_{sh}) \right]$$

$$= (78) \begin{cases} \text{Look up on shaft magnetization curve} \\ \text{given in (18) at density (113)} \end{cases}$$

(118)

 Φ_5 COIL LEAKAGE FLUX

$$\begin{aligned} \Phi_5 &= (P_5) \left[(F_{g2}) + 2(F_g) + 2(F_T) + 2(F_C) + (F_{g3}) \right] \times 10^{-3} \\ &= (84) \left[(123) + 2(96) + 2(97) + 2(98) + (120) \right] \times 10^{-3} \end{aligned}$$

(119)

 B_{g3} AUXILIARY AIR GAP (g_3) DENSITY - Note the flux

crossing air gap (g_2) is equal the flux crossing air gap (g_3)

$$B_{g3} = \frac{\Phi_{g2}}{A_{g3}} = \frac{(108)}{(70a)}$$

(120)

 F_{g3} AUXILIARY AIR GAP (g_3) AMPERE TURNS

$$F_{g3} = \frac{(B_{g3})(g_3)(10^3)}{3.19} = \frac{(119)}{3.19} (59b) \times 10^3$$

(120a)	--	<u>YODE</u> - No provision is made in this manual for calculating the flux densities in the section designated y_1 and y_2 in the accompanying sketch. Make sure that the underside periphery of the pole base times the thickness of the flux plate y_1 is equal to the cross-section of the pole base; or that the flux plate is equal to the pole thickness. The pole areas are assumed to be equal.
(122)	B_{g2}	<u>AUXILIARY GAP (g_2) DENSITY</u>
		$B_{g2} = \frac{\Phi_{g2}}{A_{g2}} = \frac{(108)}{(70)}$
(123)	F_{g2}	<u>AUXILIARY AIR GAP (g_2) AMPERE TURNS</u>
		$F_{g2} = \frac{(B_{g2})}{3.19} (g_2) \times 10^3 = \frac{(122)}{3.19} (59a) \times 10^3$
(127)	F_{NL}	<u>TOTAL AMPERE TURNS</u> - at no load. The total ampere turns per pole required to produce rated voltage at no load.
		$F_{NL} = 2(F_g) + 2(F_T) + 2(F_c) + (F_{sh})$ $= 2(96) + 2(97) + 2(98) + (114)$

(127a)	I_{FNL}	<u>FIELD CURRENT</u> - at no load. $I_{FNL} = (F_{NL})/(N_F) = (127)/(146)$
(127b)	E_F	<u>FIELD VOLTS</u> - at no load. This calculation is made with cold field resistance at 20°C for no load condition. $E_F = (I_{FNL})(R_f \text{ cold}) = (127a)(154)$
(127c)	S_F	<u>CURRENT DENSITY</u> - at no load. Amperes per square inch of field conductor. $S_F = (I_{FNL})/(a_{cf}) = (127)/(153)$
(128)	A	<u>AMPERE CONDUCTORS</u> per inch - The effective ampere conductors per inch of stator periphery. This factor indicates the "specific loading" of the machine. Its value will increase with the rating and size of the machine and also will increase with the number of poles. It will decrease with increases in voltage or frequency. A is generally higher in single phase machines than in polyphase ones. $A = \frac{(I_{PH})(n_S)(K_P)}{(C)(\gamma_S)} = \frac{(8)(30)(44)}{(32)(26)}$

(129)

X

REACTANCE FACTOR - The reactance factor is the quantity by which the specific permeance must be multiplied to give percent reactance. It is the percent reactance for unit specific permeance, or the percent of normal voltage induced by a fundamental flux per pole per inch numerically equal to the fundamental armature ampere turns at rated current. Specific permeance is defined as the average flux per pole per inch of core length produced by unit ampere turns per pole.

$$X = \frac{100(A)(K_d)}{2(C_1)(B_g) \times 10^3} = \frac{100(128)(43)}{2(71)(95) \times 10^3}$$

(130)

 X_L

LEAKAGE REACTANCE - The leakage reactance of the stator for steady state conditions. When $(5) = 3$, calculate as follows:

$$X_L = X[(\lambda_i) + (\lambda_E)] = (129)[(62) + (64)]$$

In the case of two phase machines a component due to belt leakage must be included in the stator leakage reactance. This component is due to the harmonics caused by the concentration of the MMF into a small number of phase belts per pole and is negligible for three phase machines. When $(5) = 2$, calculate as follows:

$$\lambda_B = \frac{0.1(d)}{(P)(g_e)} \left[\frac{\sin \left[\frac{3(y)}{(m)(q)} \right] 90^\circ}{(K_P)} \right] = \frac{0.1(11)}{(6)(69)} \left[\frac{\sin \frac{3(31)}{(5)(25)} 90^\circ}{(44)} \right]$$

$X_\lambda = X [(\lambda_i) + (\lambda_E) + (\lambda_B)]$ where $\lambda_B = 0$ for 3 phase machines.

$$X_\lambda = (129) [(62) + (64) + (130)]$$

(131) x_{ad} REACTANCE - direct axis - This is the fictitious reactance due to armature reaction in the direct axis.

$$x_{ad} = \frac{.9(N_e)(I_{PH})(C_M)(K_d)}{(P)[(2F_g) + (F_{g2}) + (F_{g3})]} = \frac{.9(45)(8)(74)(43)}{6[2(96) + (123) + (120)]}$$

(132) x_{aq} REACTANCE - quadrature axis - This is the fictitious reactance due to armature reaction in the direct axis.

$$x_{aq} = \frac{(C_q)(x_{ad})}{(C_m)(C_1)} = \frac{(71)(81)}{(74)(75)}$$

(133) x_d SYNCHRONOUS REACTANCE - direct axis - The steady state short circuit reactance in the direct axis.

$$x_d = (x_\lambda) + (x_{ad}) = (130) + (131)$$

(134) x_q SYNCHRONOUS REACTANCE - quadrature axis - The steady state short circuit reactance in the quadrature axis.

$$x_q = (x_\lambda) + (x_{aq}) = (130) + (132)$$

(145)	V_r	<u>PERIPHERAL SPEED</u> - The velocity of the rotor surface in feet per minute
		$V_r = \frac{\pi (d_r)(RPM)}{12} = \frac{\pi(11a)(7)}{12}$
(146)	N_F	<u>NUMBER OF FIELD TURNS TOTAL</u>
(147)	ℓ_{tf}	<u>MEAN LENGTH OF FIELD TURN</u>
(148)	--	<u>FIELD CONDUCTOR DIA OR WIDTH</u> in inches
(149)	--	<u>FIELD CONDUCTOR THICKNESS</u> in inches - Set this item = 0 for round conductor
(150)	$X_f^{\circ}\text{C}$	<u>FIELD TEMP IN $^{\circ}\text{C}$</u> - Input temp at which full load field loss is to be calculated.
(151)	ρ_f	<u>RESISTIVITY</u> of field conductor @ 20°C in micro ohm- inches. Refer to table given in Item (51) for conversion factors.
(152)	ρ_f (hot)	<u>RESISTIVITY</u> of field conductor at $X_f^{\circ}\text{C}$ $\rho_f \text{ (hot)} = \rho_f \left[\frac{(X_f^{\circ}\text{C}) + 234.5}{254.5} \right] = (104) \left[\frac{(150) + 234.5}{254.5} \right]$

(153)	a_{cf}	<u>CONDUCTOR AREA OF FIELD WINDING</u> - Calculate same as stator conductor area (46) except substitute (102) for (39) (101) for (33)
(154)	R_f (cold)	<u>COLD FIELD RESISTANCE @ 20°C</u> $R_f \text{ (cold)} = (\rho_f) \frac{(N_f)(\ell_{tf})}{(a_{cf})} = (104) \frac{(146)(147)}{(153)}$
(155)	R_f (hot)	<u>HOT FIELD RESISTANCE</u> - Calculated at X_f^0 C (103) $R_f \text{ (hot)} = (\rho_f \text{ hot}) \frac{(N_f)(\ell_{tf})}{(a_{cf})} = (105) \frac{(99)(100)}{(106)}$
(156)	--	<u>WEIGHT OF FIELD COPPER</u> in lbs #'s of copper = $.321(N_f)(\ell_{tf})(a_{cf})$ $= .321(146)(147)(153)$ <i>NOTE: ALSO REFER TO NOTE GIVEN IN ITEM (65)</i>
(157)	--	<u>WEIGHT OF ROTOR IRON</u> - Because of the large number of different pole shapes, one standard formula cannot be used for calculating rotor iron weight. Therefore, the computer will not calculate rotor iron weight. The space is allowed on the input sheet for record purposes only. By inserting 0. in the space allowed for rotor iron weight, the computer will show "0" on the

output sheet. If the rotor iron weight is available and inserted on input sheet, then the output sheet will show this same weight on the output sheet.

(160) X_F

THE EFFECTIVE FIELD LEAKAGE REACTANCE (X_F)

The reactance which added to the stator leakage reactance gives the transient reactance X'_{du} .

When unit fundamental armature ampere turns are suddenly applied on the direct axis, an initial field current (I_f) will be induced. The value of this initial field current will be just enough to make the net flux interlinking the field because of the field current and the armature current zero. The field ampere turns will equal the armature ampere turns.

$$X_F = (X) \frac{(P)}{(l)} \left[\frac{\left(C_1 \right)^2}{\left(C_P \right)} \frac{\left(P_g \right)^2}{2 \pi (P_e) \left[\frac{g'}{g} e \right]^2} \right] \times 10^{-6}$$

$$X_F = (79) \frac{(6)}{(17)} \left[\frac{\left(\frac{(71)}{(73)} \right)^2}{2 \pi (160a)} \frac{(160)}{\left[\frac{(160)}{(69)} \right]^2} \right] \times 10^{-6}$$

$$\text{Where } P_g = \frac{3.19(\tau_p)(\ell_s)(C_p)}{(g_e)} = \frac{3.19(41)(17)(73)}{(69)}$$

$$\text{Where } g'_e = (g_e) \left[\frac{2(F_g) + (F_{g2}) + (F_{g3})}{2(F_g)} \right] = (69) \left[\frac{2(96) + (123) + (120)}{2(96)} \right]$$

(160a) P_e FIELD LEAKAGE PERMEANCE

$$P_e = P_1 + P_2 + P_3 + P_4 + P_5$$

$$= (80) + (81) + (82) + (83) + (84)$$

(160b) P_r ROTOR LEAKAGE PERMEANCE

$$P_r = (P_1) + (P_2) + (P_3) + (P_4)$$

$$= (80) + (81) + (82) + (83)$$

(161) L_f FIELD SELF-INDUCTANCE

$$L_f = (N_c)^2 \quad P_e = 2(146)^2(160a)$$

(166) X'_{du} UNSATURATED TRANSIENT REACTANCE

$$X'_{du} = (X_d) + (X_f) = (80) + (112)$$

(167) X'_d SATURATED TRANSIENT REACTANCE

$$X'_d = .88(X'_{du}) = .88(166)$$

(168)	X''_d	<u>SUBTRANSIENT REACTANCE</u> in direct axis
		$X''_d = (X'_d) = (167)$
(169)	X''_q	<u>SUBTRANSIENT REACTANCE</u> in quadrature axis
		$X''_q = X_q = (134)$
(170)	X_2	<u>NEGATIVE SEQUENCE REACTANCE</u> - The reactance due to the field which rotates at synchronous speed in a direction opposite to that of the rotor.
		$X_2 = .5 [X''_d + X''_q] = .5 [(168) + (169)]$
(172)	X_0	<u>ZERO SEQUENCE REACTANCE</u> - The reactance drop across any one phase (star connected) for unit current in each of the phases. The machine must be star connected for otherwise no zero sequence current can flow and the term then has no significance.
		If (28) = 0 Then $X_0 = 0$
		If (28) ≠ 0 Then
		$X_0 = X \left\{ \frac{(K_{X0})}{(K_{X1})} [(λ_i) + (λ_{Bo})] + \frac{1.667[(h_1) + 2(h_3)]}{(m)(q)(K_P)^2(K_d)^2(b_S)} + .2(λ_E) \right.$
		$= (79) \left\{ \frac{(173)}{(174)} [(62) + (175)] + \frac{1.667 [(22) + 2(22)]}{(5)(25)(44)^2(43)^2(22)} + .2(64) \right\}$

(173)	K_{X0}	If $(30) = 1$ Then $K_{X0} = 1$ If $(30) \neq 1$ Then $K_{X0} = \frac{3(Y)}{(m)(q)} - 2$ $= \frac{3(31)}{(5)(25)} - 2$
(174)	K_{X1}	If $(30) = 1$ Then $K_{X1} = 1$ If $(30) \neq 1$ Then: $K_{X1} = \left[\frac{3(Y)}{4(m)(q)} + \frac{1}{4} \right] = \left[\frac{3(31)}{4(5)(25)} + \frac{1}{4} \right]$ If $(31a) \geq .667$ $K_{X1} = \left[\frac{3(Y)}{4(m)(q)} - \frac{1}{4} \right] = \left[\frac{3(31)}{4(5)(25)} - \frac{1}{4} \right]$ If $(31a) < .667$
(175)	λ_{Bo}	$\lambda_{Bo} = \frac{(K_{X0})}{(K_P)^2} [.07(\lambda_a)] = \frac{(173)}{(44)^2} [.07(175)]$ Where $\lambda_a = \frac{6.38(d)}{(P)(g_e)} = \frac{6.38(11)}{6(69)}$
(176)	T'_{do}	<u>OPEN CIRCUIT TIME CONSTANT</u> - The time constant of the field winding with the stator open circuited and with negligible external resistance and inductance in the field circuit. Field resistance at room temperature (20°C) is used in this calculation. $T'_{do} = \frac{L_F}{R_F} = \frac{(161)}{(154)}$

(177)	T_a	<u>ARMATURE TIME CONSTANT</u> - Time constant of the D.C. component. In this calculation stator resistance at room temperature (20°C) is used.
		$T_a = \frac{X_2}{200 \pi(f)(r_a)} = \frac{(170)}{200 \pi(5a)(177)}$
		Where: $r_a = \frac{(m)(I_{PH})^2(R_{SPH} \text{ cold})}{\text{Rated KVA}} = \frac{(5)(8)^2(53)}{(2)}$
(178)	T'_d	<u>TRANSIENT TIME CONSTANT</u> - The time constant of the transient reactance component of the alternating wave.
		$T'_d = \frac{(X'_d)}{(X_d)} (T'_{do}) = \frac{(167)}{(133)} (176)$
(180)	F_{SC}	<u>SHORT CIRCUIT AMPERE TURNS</u> - The field ampere turns required to circulate rated stator current when the stator is short circuited.
		$F_{SC} = (X_d)(F_g) = (133)(96)$
(181)	SCR	<u>SHORT CIRCUIT RATIO</u> - The ratio of the field current to produce rated voltage on open circuit to the field current required to produce rated current on short circuit.

Since the voltage regulation depends on the leakage reactance and the armature reaction, it is closely related to the current which the machine produces under short circuit conditions, and, therefore, is directly related to the SCR.

$$\text{SCR} = \frac{F_{NL}}{F_{SC}} = \frac{(127)}{(180)}$$

(182) I^2R_F FIELD I^2R - at no load. The copper loss in the field winding is calculated with cold field resistance at 20°C for no load condition.

$$\text{Field } I^2R = (I_{FNL})^2 (R_f \text{ cold}) = (127a)^2 \quad (154)$$

(183) F&W FRICTION & WINDAGE LOSS - The best results are obtained by using existing data. For ratioing purposes, the loss can be assumed to vary approximately as the $5/2$ power of the rotor diameter and as the $3/2$ power of the RPM. When no existing data is available, the following calculation can be used for an approximate answer. Insert 0. when computer is to calculate F&W. Insert actual F&W when available. Use same value for all load conditions.

$$F&W = 2.52 \times 10^{-6} (d_r)^{2.5} (\ell_p) (RPM)^{1.5}$$

$$= 2.52 \times 10^{-6} (11a)^{2.5} (76) (7)^{1.5}$$

- (184) W_{TNL} STATOR TEETH LOSS - at no load. The no load loss (W_{TNL}) consists of eddy current and hysteresis losses in the iron. For a given frequency the no load tooth loss will vary as the square of the flux density.

$$W_{TNL} = .453(b_t 1/3)(Q)(\ell_s)(h_s)(K_Q)$$

$$= .453(57a)(23)(17)(22)(184)$$

$$\text{Where } K_Q = (k) \left[\frac{(B_t)}{(B)} \right]^2 = (19) \left[\frac{(91)}{(20)} \right]^2$$

- (185) W_c STATOR CORE LOSS - The stator core losses are due to eddy currents and hysteresis and do not change under load conditions. For a given frequency the core loss will vary as the square of the flux density (B_c).

$$W_c = 1.42 \left[(D) - (h_c) \right] (h_c)(\ell_s)(K_{Q1})$$

$$= 1.42 \left[(12) - (24) \right] (24)(17)(185)$$

$$\text{Where } K_{Q1} = (k) \left[\frac{(B_c)}{(B)} \right]^2 = (19) \left[\frac{(94)}{(20)} \right]^2$$

(186)

W_{NPL}

POLE FACE LOSS - at no load. The pole surface losses are due to slot ripple caused by the stator slots. They depend upon the width of the stator slot opening, the air gap, and the stator slot ripple frequency. The no load pole face loss (W_{PNL}) can be obtained from Graph 2. Graph 2 is plotted on the bases of open slots. In order to apply this curve to partially open slots, substitute b_0 for b_s . For a better understanding of Graph 2, use the following sample:

K_1 as given on Graph 2 is derived empirically and depends on lamination material and thickness. Those values given on Graph 2 have been used with success. K_1 is an input and must be specified. See Item (151) for values of K_1 .

K_2 is shown as being plotted as a function of $(B_G)^{2.5}$. Also note that upper scale is to be used. Another note in the lower right hand corner of graph indicates that for a solid line (____), the factor is read from the left scale, and for a broken or dashed line (____ - ____),

the right scale should be read. For example, find K_2 when $B_G = 30$ kilolines. First locate 30 on upper scale. Read down to the intersection of solid line plot of $K_2 = f(B_G)^{2.5}$. At this intersection read the left scale for K_2 . $K_2 = .28$. Also refer to Item (188) for K_2 calculations.

K_3 is shown as a solid line plot as a function of $(F_{SLT})^{1.65}$. The note on this plot indicates that the upper scale X 10 should be used.

Note F_{SLT} = slot frequency. For an example, find K_3 when $F_{SLT} = 1000$. Use upper scale X10 to locate 1000. Read down to intersection of solid line plot of $K_3 = f(F_{SLT})^{1.65}$. At this intersection read the left scale for K_3 . $K_3 = 1.35$. Also refer to Item (189) for K_3 calculations.

For K_4 use same procedure as outlined above except use lower scale. Do not confuse the dashed line in this plot with the note to use the right scale. The note does not apply in this case. Read left scale. Also refer to Item (190) for K_4 calculations.

For K_5 use bottom scale and substitute b_o for b_s when using partially closed slot.

Read left scale when using solid plot. Use right scale when using dashed plot. Also refer to Item (191) for K_5 calculations.

For K_6 use the scale attached for C_1 and read K_6 from left scale. Also refer to Item (192) for K_6 calculations.

The above factors (K_2), (K_3), (K_4), (K_5), (K_6) can also be calculated as shown in (188), (189), (190), (191), (192) respectively.

$$\begin{aligned} W_{PNL} &= \pi(d)(\ell)(K_1)(K_2)(K_3)(K_4)(K_5)(K_6) \\ &= \pi(11)(13)(187)(188)(189)(190)(191)(192) \end{aligned}$$

- (187) K_1 K_1 is derived empirically and depends on lamination material and thickness. The values used successfully for K_1 are shown on Graph 2. They are:

$$\begin{aligned} K_1 &= 1.17 \text{ for .028 lam thickness, low carbon steel} \\ &= 1.75 \text{ for .063 lam thickness, low carbon steel} \\ &= 3.5 \text{ for .125 lam thickness, low carbon steel} \\ &= 7.0 \text{ for solid core} \end{aligned}$$

K_1 is an input and must be specified on input sheet.

(188) K_2 K_2 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

$$K_2 = f(B_G) = 6.1 \times 10^{-5} (B_G)^{2.5}$$

$$= 6.1 \times 10^{-5} (95)^{2.5}$$

(189) K_3 K_3 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

$$K_3 = f(F_{SLT}) = 1.5147 \times 10^{-5} (F_{SLT})^{1.65}$$

$$= 1.5147 \times 10^{-5} (189)^{1.65}$$

$$\text{Where } F_{SLT} = \frac{(RPM)}{60} (Q)$$

$$= \frac{(7)}{60} (23)$$

(190) K_4 K_4 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

For $T_s \leq .9$

$$K_4 = f(T_s) = .81(T_s)^{1.285}$$

$$= .81(26)^{1.285}$$

For $.9 \leq T_s \leq 2.0$

$$K_4 = f(T_s) = .79(T_s)^{1.145}$$

$$= .79(26)^{1.145}$$

For $T_s > 2.0$

$$K_4 = f(T_s) = .92(T_s)^{.79}$$

$$= .92(26)^{.79}$$

- (191) K_5 can be obtained from Graph 2 (see Item 186 for explanation of Graph 2) or it can be calculated as follows:

For $(b_s)/(g) \leq 1.7$

$$K_5 = f(b_s/g) = .3 [(b_s/g)]^{2.31}$$

$$= .3 [(22)/(59)]^{2.31}$$

NOTE: For partially open slots substitute b_o for b_s in equations shown.

For $1.7 < (b_s)/(g) \leq 3$

$$K_5 = f(b_s/g) = .35 [(b_s/g)]^2$$

$$= .35 [(22)/(59)]^2$$

For $3 < (b_s)/(g) \leq 5$

$$K_5 = f(b_s/g) = .625 [(b_s/g)]^{1.4}$$

$$= .625 [(22)/(59)]^{1.4}$$

For $(b_s)/(g) > .5$

$$K_5 = f \left[(b_s)/(g) \right] = 1.38 \left[(b_s)/(g) \right] .965$$

$$= 1.38 \left[(22)/(59) \right] .965$$

- (192) K₆ K₆ can be obtained from Graph 2 (see item 186 for explanation of Graph 2) or it can be calculated as follows:

$$K_6 = f(C_1) = 10 \left[9323(C_1) - 1.60596 \right]$$

$$= 10 \left[.9323(71) - 1.60596 \right]$$

- (194) I²R STATOR I²R - at no load. This item = 0. Refer to Item (245) for 100% load stator I²R.

- (195) -- EDDY LOSS - at no load. This item = 0. Refer to Item (246) for 100% load eddy loss.

- (196) -- TOTAL LOSSES - at no load. Sum of all losses.

$$\begin{aligned} \text{Total Losses} &= (\text{Field } I^2R) + (\text{F&W}) + (\text{Stator Teeth Loss}) \\ &\quad + (\text{Stator Core Loss}) + (\text{Pole Face Loss}) \\ &= (182) + (183) + (184) + (185) + (186) \end{aligned}$$

NOTE: The output sheet shows the next items to be: (Rating), (Rating + Losses), (% Losses), (% Efficiency). These items

do not apply to the no load calculation since the rating is zero. Refer to Items (175), (176), (177), (178) for these calculations under load.

The N. L. calculations should all be repeated now for 100% load.

(196a) ϕ_{qq}

LEAKAGE FLUX PER POLE at 100% load

$$\begin{aligned}\phi_{qq} &= \phi_q \left\{ \frac{(e_d)(F_g) + [1 + \cos(\theta)] (F_T) + (F_C)}{(F_g) + (F_T) + (F_C)} \right. \\ &\quad \left. = (100) \frac{(198)(96) + [1 - \cos(198a)] (97) + (98)}{(96) + (97) + (98)} \right.\end{aligned}$$

(198) e_d

Where $e_d = \cos \epsilon + (X_d) \sin \psi$

$$= \cos(198a) + (83) \sin(198b)$$

(198a) θ

Where $\theta = \cos^{-1} [(\text{Power Factor})]$

$$= \cos^{-1} [(9)]$$

Where $\psi = \tan^{-1} \left[\frac{\sin(\theta) + (X_q)/(100)}{\cos(\theta)} \right]$

$$= \tan^{-1} \left[\frac{\sin(198a) + (134)/(100)}{\cos(198a)} \right]$$

Where $\epsilon = \psi - \theta = (198a) - (198a)$

(207)

 ϕ_{7L} FLUX LEAKAGE FROM STATOR TO ROTOR

$$\begin{aligned}\phi_{7L} &= 2(P_7) \left[(e_d)(F_g) + (F_T) [1 + \cos(\theta)] + (F_C) \right] \times 10^{-3} \\ &= 2(86) \left[(198a)(96) + (97) [1 + \cos(198b)] + (98) \right] \times 10^{-3}\end{aligned}$$

(213)

 ϕ_{PL} FLUX PER POLE at 100% load

For P. F. .0 to .95

$$\begin{aligned}\phi_{PL} &= (\phi_P) \left[(e_d) - \frac{.93(X_{ad})}{100} \sin(\psi) \right] \\ &= (92) \left[(198) - \frac{.93(131)}{100} \sin(198a) \right]\end{aligned}$$

For P. F. .95 to 1.0

$$\phi_{PL} = (\phi_P)(K_C) = (92)(9a)$$

(213a)

 ϕ_{PTL} TOTAL FLUX PER POLE at 100% load

$$\phi_{PTL} = \phi_{PL} + \phi_{qL} = (213) + (196a)$$

(213b)

 B_{PL} FLUX DENSITY AT BASE OF POLE at 100% load

$$B_{PL} = \frac{\phi_{PTL}}{a_p} = \frac{(213a)}{(79)}$$

(213c)

 F_{PL} AMPERE TURNS PER POLE at 100% load

$$F_{PL} = (\ell_p) \left[NI/\text{in} @ \text{density } (B_{PL}) \right]$$

$$= (76) \left[\begin{array}{l} \text{Look up ampere turns/inch on rotor} \\ \text{magnetization curve given in (18) at} \\ \text{density (213b)} \end{array} \right]$$

(221)	Φ_{g2L}	<u>TOTAL FLUX IN AUXILIARY AIR GAP under load</u>
		$\Phi_{g2L} = (\Phi_{PTL}) \frac{(P)}{2} + \frac{(\Phi_{7L})}{2}$
		$= (213a) \frac{(6)}{2} + \frac{(207)}{2}$
(224)	B_{g2L}	<u>FLUX DENSITY IN AUXILIARY AIR GAP under load</u>
		$B_{g2L} = \frac{\Phi_{g2L}}{(A_{g2})} = \frac{(221)}{(70)}$
(225)	F_{g2L}	<u>AUXILIARY AIR GAP AMPERE TURN DROP under load</u>
		$F_{g2L} = (B_{g2L}) \frac{(g_2)}{3.19} \times 10^3 = (224) \frac{(59a)}{3.19} \times 10^3$
(226)	Φ_{5L}	<u>COIL LEAKAGE FLUX UNDER LOAD</u>
		$\Phi_{5L} = P_5 \left[2(e_d)(F_g) + (F_{g2L}) + (F_{g3L}) + 2(F_T) \left[1 + \cos(\theta) \right] \right] \times 10^{-3}$
		$= (84) \left[2(198)(96) + (225) + (231) + 2(97) \left[1 + \cos(198a) \right] \right] \times 10^{-3}$
(230)	B_{g3L}	<u>AUXILIARY GAP (g_3) FLUX DENSITY - note the flux in air gap (g_2) is equal to flux in gap (g_3)</u>
		$B_{g3L} = \frac{(\Phi_{g2L})}{(A_{g3})} = \frac{(221)}{(70a)}$

(231)	F_{g3L}	<u>AUXILIARY GAP (g_3) AMPERE TURN DROP under load</u>
		$F_{g3L} = \frac{(B_{g3L})(g_3)}{3.19} \times 10^3 = \frac{(230)(59b)}{3.19} \times 10^3$
(231a)	ϕ_{SHL}	<u>SHAFT FLUX</u>
		$\phi_{SHL} = (\phi_{g2L}) + (\phi_{5L}) = (221) + (226)$
(232)	B_{SHL}	<u>SHAFT DENSITY</u>
		$B_{SHL} = \frac{\phi_{SHL}}{(A_s)} = \frac{(231a)}{(112)}$
(233)	F_{SHL}	<u>SHAFT AMPERE TURN DROP</u>
		$F_{SHL} = (l_{SH}) \left[NI/inch @ (B_{SHL}) \right]$
		$= (78) \left[\begin{array}{l} \text{Look upon shaft magnetization curve @} \\ \text{density (232)} \end{array} \right]$
(236)	F_{FL}	<u>TOTAL AMPERE TURNS PER POLE under load</u>
		$F_{FL} = (F_{SHL}) + (F_{g2L}) + (F_{g3L}) + 2(F_g)(e_d) + 2(F_T) \left[1 + \cos(\theta) \right]$
		$= (233) + (225) + (231) + 2(96)(198) + 2(97) \left[1 + \cos(198a) \right]$
(237)	I_{FFL}	<u>FIELD AMPERES under load</u>
		$I_{FFL} = \frac{(F_{FL})}{(N_F)} = \frac{(236)}{(146)}$
(239)	--	<u>CURRENT DENSITY at 100% load</u>
		Current Density = $(I_{FFL})/(a_{cf}) = (237)/(153)$

(238)	E_{FFL}	<u>FIELD VOLTS</u> at 100% load - This calculation is made with hot field resistance at expected temperature at 100% load. Field Volts = $(I_{FFL})(R_f \text{ hot}) = (237)(155)$
(241)	$I^2 R_{FL}$	<u>FIELD $I^2 R$</u> at 100% load - The copper loss in the field winding is calculated with hot field resistance at expected temperature for 100% load condition. Field $I^2 R = (I_{FFL})^2 (R_F \text{ hot}) = (237)^2 (155)$
(242)	W_{TFL}	<u>STATOR TEETH LOSS</u> at 100% load - The stator tooth loss under load increases over that of no load because of the parasitic fluxes caused by the ripple due to the rotor damper bar slot openings. $W_{TFL} = \left\{ 2 \left[.27(X_d) + \frac{(\% \text{ Load})}{100} \right]^{1.8} + 1 \right\} (W_{TNL})$ NOTE (X_d) is in per unit $= \left\{ 2 \left[.27(133) 1 \right]^{1.8} + 1 \right\} (184)$
(243)	W_{PFL}	<u>POLE FACE LOSS</u> at 100% load $W_{PFL} = \left\{ \left[\frac{(K_{SC})(I_{PH}) \frac{(\% \text{ Load})}{100} (n_s)}{(C)(F_g)} \right]^2 + 1 \right\} (W_{PNL})$

$$= \left\{ \left[\frac{(242)(8) 1 (30)}{(32)(96)} \right]^2 + 1 \right\} (186)$$

(K_{SC}) is obtained from Graph 3

- (245) I^2R_L STATOR I^2R at 100% load - The copper loss based on the D. C. resistance of the winding. Calculate at the maximum expected operating temperature.

$$I^2R = (m)(I_{PH})^2 (R_{SPH \text{ hot}}) \frac{(\% \text{ Load})}{100}$$

$$= (5)(8)^2 (54) 1.$$

- (246) -- EDDY LOSS - Stator I^2R loss due to skin effect

$$\begin{aligned} \text{Eddy Loss} &= \left[\frac{(EF_{top}) + (EF_{bot})}{2} - 1 \right] (\text{Stator } I^2R) \\ &= \left[\frac{(55) + (56)}{2} - 1 \right] (173) \end{aligned}$$

- (247) -- TOTAL LOSSES at 100% load - sum of all losses at 100% load.

$$\begin{aligned} \text{Total Losses} &= (\text{FIELD } I^2R) + (\text{F&W}) + (\text{Stator Teeth Loss}) \\ &\quad + (\text{Stator Core Loss}) + (\text{Pole Face Loss}) \\ &\quad + (\text{Stator } I^2R) + (\text{Eddy Loss}) \\ &= (241) + (183) + (242) + (185) + (243) + (245) + (246) \end{aligned}$$

- (248) -- RATING IN KW at 100% load

$$\begin{aligned} \text{Rating} &= 3(E_{PH})(I_{PH}) \quad (\text{P. F.}) \frac{(\% \text{ Load})}{100} \times \frac{1}{1000} \\ &= 3(4)(8) \quad . (9)(1.) \times \frac{1}{1000} \end{aligned}$$

$$(249) \quad \text{--} \quad \text{RATING & LOSSES} = (248) + (247) \times 10^{-3}$$

$$(250) \quad \text{--} \quad \% \text{ LOSSES} = \frac{\text{Losses}}{1000} / (\text{Rating} + \text{Losses}) \times 100$$

$$= \frac{(247)}{1000} / (249) \times 100$$

$$(251) \quad \text{--} \quad \% \text{ EFFICIENCY} = 100\% - \% \text{ Losses}$$

$$= 100\% - (250)$$

Item (160) through (178) are 100% load calculations.

These items can be recalculated for any load condition by simply inserting the values that correspond to the % load being calculated. The factor $\frac{(\% \text{ Load})}{100}$ takes care of (I_{PH}) as it changes with load.

Note that values for F&W (183) and W_C (Stator Core Loss) (185) do not change with load, therefore, they can be calculated only once.

SUPPLEMENT TO DESIGN MANUAL FOR PERMEANCE CALCULATIONS

Permeance (P) is the property of a magnetic circuit, or any part of a circuit, which determines the total flux corresponding to a given mmf as indicated in the expression -

$$\Phi = F P = \text{mmf} \times \text{permeance}$$

From "Standard Handbook for Electrical Engineers" A. E. Knowlton, 7th edition, McGraw-Hill, Section 4-310

Magnetic Permeability (μ) is that property of an isotropic medium which determines under specified conditions, the magnitude relation between magnetic induction and magnetizing force in the medium usually expressed -

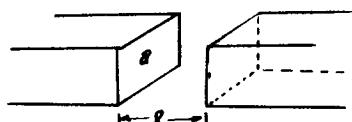
$$\mu = \frac{B}{H}$$

Same reference Section 4-308.

For air $\mu = 3.19$ $\frac{\text{Flux Line/inch}^2}{\text{Ampere Turns/inch}}$

The following formulas are from Roter's "Electromagnetic Devices"

Parallel planes of infinite extent

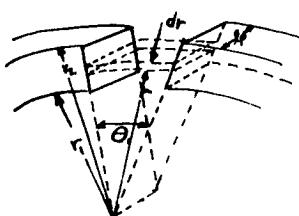


$$P = \mu \frac{A}{l}$$

where A = area

l = length of flux path

Non-parallel planes of infinite extent

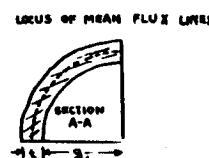
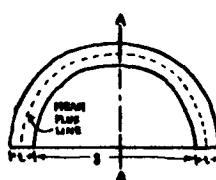


$$dP = \mu \frac{l p}{\theta} dr$$

$$P = \mu \frac{l p}{\theta} \int_{r_1}^{r_2} dr$$

$$P = \mu \frac{l p}{\theta} \ln \frac{r_2}{r_1}$$

QUADRANT OF SPHERICAL SHELL



Mean length of flux path is $\frac{\pi}{2} (t+g)$

Maximum area of flux path is -

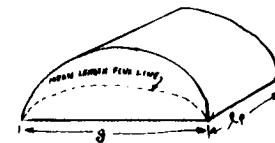
$$\frac{\pi (t+g)^2}{4} - \frac{\pi g^2}{16} = \frac{\pi}{4} (t^2 + tg)$$

Average area of path is considered to be -

$$\frac{\pi}{8} t (t+g) \text{ and } P = \frac{\mu g}{l} = \frac{\mu \frac{\pi}{8} t (t+g)}{\frac{\pi}{2} (t+g)} = \frac{\mu t}{4}$$

Special formulas for use in estimating permeances of flux paths.

SEMI-CIRCULAR CYLINDRICAL VOLUME



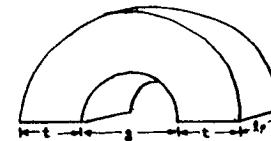
Mean length of flux line has been found by graphical measurement to be 1.22 g.

Mean area of flux path found by dividing the entire volume by mean length of flux path is,

$$\text{Mean area} = \frac{\pi g^2 l p}{8} \times \frac{1}{1.22 g} = 0.322 g l p$$

$$P = \frac{\mu g}{l} = \frac{0.322 g l p}{1.22 g} = 0.26 g l p$$

HALF ANNULUS



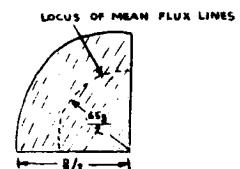
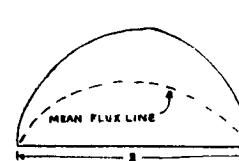
NOTE: IN THE COMPUTER DESIGN MANUAL THE SYMBOL g WAS CHANGED TO z TO AVOID CONFUSION WITH g (AIR GAP)

Assume the mean length of the flux path to be $\pi \frac{(z+t)}{2}$ and the average area of the path to be $\frac{\pi z}{4} l p$, then

$$P = \frac{\mu g}{l} = \frac{2 \mu z l p}{\pi (z+t)} = 0.64 \frac{\mu l p}{(\frac{z}{t} + 1)}$$

$$\text{WHEN } z < 3t \quad P = \frac{\mu l p}{\pi} \ln \left(1 + \frac{2t}{z} \right)$$

SPHERICAL QUADRANT



By graphical measurement, the mean flux line is 1.3 g. Volume of quadrant is $1/3 \pi (\frac{g}{2})^3$, hence mean area of flux path is -

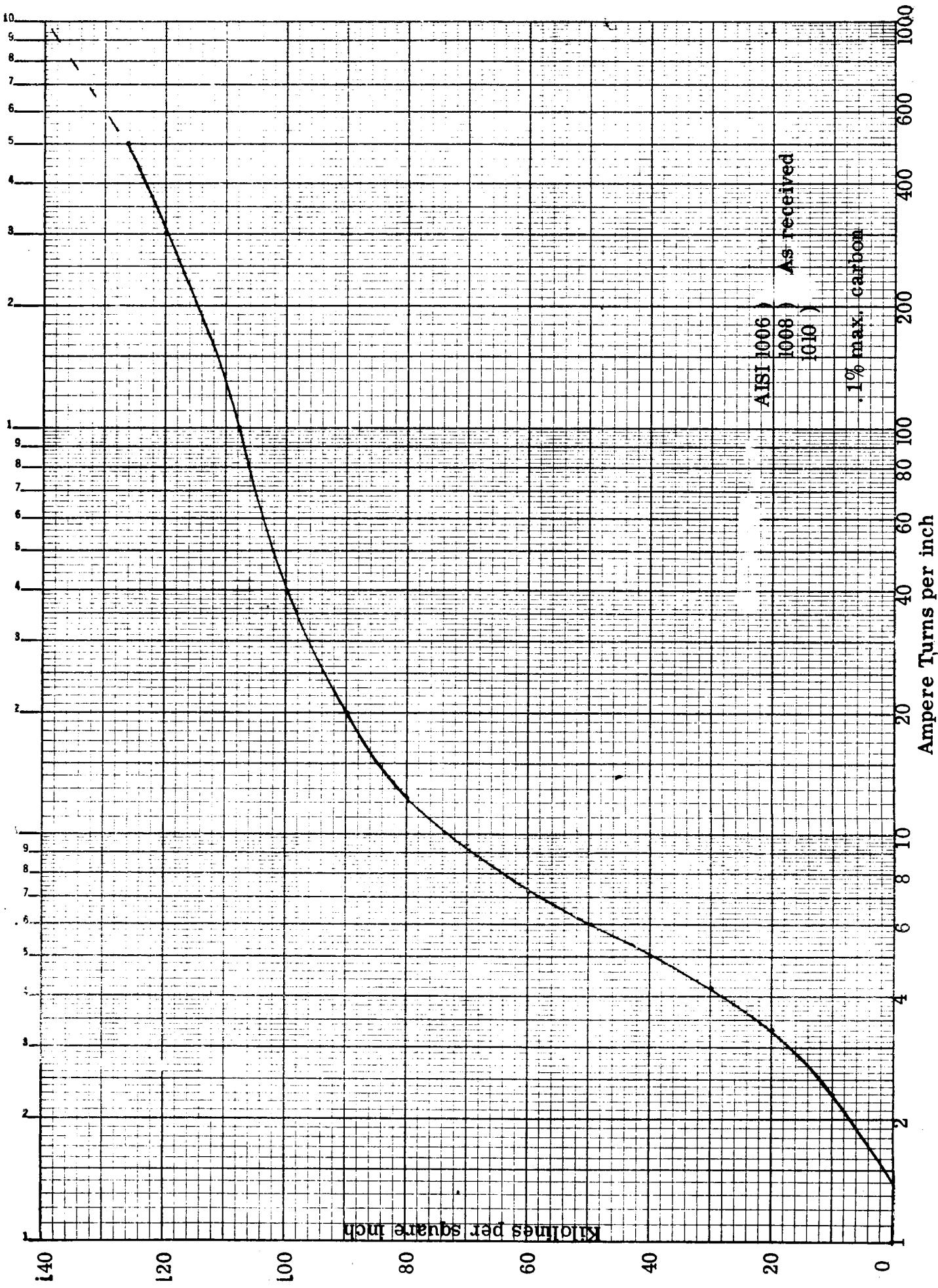
$$\frac{1}{3} \pi \left(\frac{g}{2} \right)^3 = 0.1 g^2$$

and the permeance is

$$P = \frac{\mu g}{l} = \frac{0.1 g^2 \mu}{1.3 g} = 0.077 \mu g$$

X X X

CURVE 17



PASS 1

```
1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
2 FORMAT(F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0,F7.0)
3 FORMAT(9X F12.5,2X F12.5)
7 READ2,VA,EE,EP,PN,F,PX,RPM,PI,PF,CK
    READ2, POL, D1, DU, CL, HV, BV, SF, WL, BK, ZZ
    READ2, B0, B1, B2, B3, BS, H0, HX, HY, HZ, HS
    READ2, HT, HW, QQ, W, RF, SC, YY, C, DW, SN
    READ2, SN1, DW1, DB, CE, SH, SD, PBA, SK, T1, RS
    READ2, ALG3, DG3, DG2, GC, G2, G3, C1, CW, CP, EL
    READ2, CM, CQ, PE, BP1, BP2, TP1, TP2, ALP, DR, WR
    READ2, D1, TFP, DFP, DS1, ALSH, P1, P2, P3, P4, P5
    READ2, P7, AL1, AL2, AL3, DC1, ALCO, PT, FE, RD, RT
    READ2, T2, RR, SNL, WF
    SS=SF*(CL-HV*BV)
    HC=(DU-D1-2.0*HS)*0.5
    QN=QQ/(PX*PN)
    TS=3.142*D1/QQ
    IF(ZZ-4.0)9,10,9
9  TT=(0.667*HS+D1)*3.142/QQ
    GO TO 11
10 TT=((2.0*H0+BS)*0.66+D1)*3.1416/QQ
11 IF(ZZ-1.0)12,12,13
12 CC=(5.0*GC+BS)*TS/((5.0*GC+BS)*TS-BS*BS)
    GO TO 14
13 QC=(4.44*GC+0.75*B0)*TS
    CC=QC/(QC-B0*B0)
14 CS=YY/(PN*QN)
    IF(CS-1.0)15,15,16
```

15 IF(CS-0.5)16,16,17
16 PRINT2,111.0
GO TO 7
17 TP=3.142*D1/PX
IF(SK)18,18,19
18 FS=1.0
GO TO 20
19 FS=SIN(1.571*SK/TP)*TP/(1.571*SK)
20 ZY=PX*PN
IF(PBA-60.)21,21,22
21 D=1.0
GO TO 23
22 D=2.0
23 U=0.0
24 U=U+1.0
DM=U*ZY
IF(QQ-DM)26,25,24
25 DF=SIN(1.571*D/PN)/(QN*D*SIN(1.571/(PN*QN)))
GO TO 27
26 DF=SIN(1.571*D/PN)/(QQ*D*SIN(1.571/(QQ*PN)))
27 CF=SIN(YY*1.571/(PN*QN))
EC=QQ*SC*CF*FS/C
GE=CC*GC
IF(C1)29,28,29
28 C1=0.649*LOG(PE)+1.359
29 IF(CW)30,30,31
30 CW=0.707*EE*C1*DF/(EP*PN)
31 IF(CP)32,32,33
32 CP=PE*(LOG(GC/TP)*.0378+1.191)

33 IF(EL)34,34,42
34 IF(RF)35,35,41
35 IF(PX-2.0)36,36,37
36 U=1.3
GO TO 40
37 IF(PX-4.0)38,38,39
38 U=1.5
GO TO 40
39 U=1.7
40 EL=3.142*IJ*YY*(DI+HS)/QQ+0.5
GO TO 42
41 EL=2.0*CE+3.142*(0.5*HX+DB)+YY*TS*TS/SQRT(TS*TS-BS*BS)
42 IF(CM)43,43,44
43 AA=SIN(3.142*PE)
AB=SIN(1.571*PE)*4.0
CM=(3.142*PE+AA)/AB
44 IF(CQ)45,45,46
45 AA=1.571*PE
AB=3.1416*PE
CQ=(0.5*COS(AA)+AB-SIN(AB))/(4.0*SIN(AA))
46 RB=(T1+234.5)*0.00394*RS
PRINT3,SS,CC,HC,GE,TS,C1,TT,CW,FS,CP,DF,EL,CF,CM,EC,CQ
PUNCH1,VA,EE,EP,PN,F,PX
PUNCH1,RPM,PI,PF,CK,POL,DI
PUNCH1,DU,CL,SS,HC,SF,QN
PUNCH1,WL,BK,ZZ,B0,B1,B2
PUNCH1,B3,BS,HO,HX,HY,HZ
PUNCH1,HS,HT,HW,QQ,W,RF
PUNCH1,SC,YY,C,TS,SN,DB

PUNCH1,CE,SH,SD,TT,SK,RB
PUNCH 1, ALCO,TP,D1,FE,RD,RT
PUNCH1,T2,RR,SNL,WF,PE,SN1
PUNCH1,DW1,BP1,RP2,TP1,TP2,ALP
PUNCH1,DR,WR,TFP,DFP,DS1,ALSH
PUNCH1,P1,P2,P3,P4,P5,P7
PUNCH 1,RS,GC,PT,C1,CW,CP
PUNCH 1,EL,CM,CQ,DW,CC,PBA
PUNCH 1,GE,CS,CF,FS,EC,DF
PUNCH1,ALG3,DC1,DG3,DG2,AL1,AL2
PUNCH1,AL3,ALCO,G2,G3
PAUSE
END

PASS 2

```
1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
DIMENSION DA(8),DX(6),DY(8),DZ(8)
READ1 ,VA,EE,EP,PN,F,PX
READ1 ,RPM,PI,PF,CK,POL,DI
READ1 ,DU,CL,SS,HC,SF,QN
READ1 ,WL,BK,ZZ,BO,B1,B2
READ1 ,B3,BS,H0,HX,HY,HZ
READ1 ,HS,HT,HW,QQ,W,RF
READ1 ,SC,YY,C,TS,SN,DB
READ1 ,CE,SH,SD,TT,SK,RB
READ1 , ALCO,TP,D1,FE,RD,RT
READ1 ,T2,RR,SNL,WF,PE,SN1
READ1 ,DW1,BP1,BP2,TP1,TP2,ALP
READ1 ,DR,WR,TFP,DFP,DS1,ALSH
READ1 ,P1,P2,P3,P4,P5,P7
READ1 ,RS,GC,PT,C1,CW,CP
READ1 ,EL,CM,CQ,DW,CC,PBA
READ1 ,GE,CS,CF,FS,EC,DF
READ1 ,ALG3,DC1,DG3,DG2,AL1,AL2
READ1 ,AL3,ALCO,G2,G3
DT=DW1
IF(ZZ-3.0)49,50,51
49 SM=TT-BS
GO TO 53
50 SM=(3.1416*(D1+2.*HS)/QQ)-B3
GO TO 53
51 IF(ZZ-4.0)50,52,49
52 SM=TT-BS*(0.554-0.888*H0/BS)
```

53 HM=CL+EL
IF(DT) 61,61,62
61 AC=0.785*DW*DW*SN1
GO TO 72
62 ZY=0.0
DA(1)=0.05
DA(2)=0.072
DA(3)=0.125
DA(4)=0.165
DA(5)=0.225
DA(6)=0.438
DA(7)=0.688
DA(8)=1.5
DX(1)=0.000124
DX(2)=0.00021
DX(3)=0.00021
DX(4)=0.00084
DX(5)=0.00189
DX(6)=0.00189
DY(1)=0.000124
DY(2)=0.000124
DY(3)=0.00084
DY(4)=0.00084
DY(5)=0.00189
DY(6)=0.00335
DY(7)=0.00754
DY(8)=0.03020
DZ(1)=0.000124
DZ(2)=0.000124

DZ(3)=0.000124

DZ(4)=0.00335

DZ(5)=0.00335

DZ(6)=0.00754

DZ(7)=0.0134

DZ(8)=0.0302

63 IF(DT-.05)201,200,200

200 JA=0

JB=0

JC=0

JD=0

64 JA=JA+1

JB=JB+1

JC=JC+1

JD=JD+1

IF(DT-DA(JA))65,65,64

201 D=0

IF(ZY)71,71,54

65 IF(DW-0.188)66,66,67

66 CY=DX(JB-1)

CZ=DX(JB)

GO TO 70

67 IF(DW-0.75)68,68,69

68 CY=DY(JC-1)

CZ=DY(JC)

GO TO 70

69 CY=DZ(JD-1)

CZ=DZ(JD)

70 D=CY+(CZ-CY)*(DT-DA(JA-1))/(DA(JA)-DA(JA-1))

IF(ZY)71,71,54
71 AC=(DT*DW-D)*SN1
72 IF(RT)73,73,74
73 AS=0.785*RD*RD
GO TO 55
74 ZY=1.0
DT=RT
DW=RD
GO TO 63
54 AS=RT*RD-D
55 S=PI/(C*AC)
CY=PT *FE*0.000001/AS
FK=RR*CY
FR=(T2+234.5)*FK*0.00394
RC=0.321*PT *FE*AS
IF(SH)202,203,202
203 ET=1
EB=1
GO TO 204
202 AA=0.584+(SN*SN-1.0)*0.0625*(SD*CL/(SH*HM))**2.0
AB=(SH*SC*F*AC/(BS*RB))**2.0
ET=AA*AB*0.00335+1.0
EB=ET-0.00168*AB
204 RY=SC*QQ*0.000001*HM/(PN*AC*C*C)
RG=RS*RY
RP=RB*RY
A=PI*SC*CF/(C*TS)
PUNCH1,VA,EE,EP,PN,F,PX
PUNCH1,RPM,PI,PF,CK,POL,DI

PUNCH1,DU,CL,SS,HC,SF,QN
PUNCH1,WL,BK,ZZ,BO,B1,B2
PUNCH1,B3,BS,HO,HX,HY,HZ
PUNCH1,HS,HT,HV,QQ,W,RF
PUNCH1,SC,YY,C,TS,SN,DB
PUNCH1,CE,SH,SD,TT,SK,RB
PUNCH1, ALC0,TP,D1,FE,RD,RT
PUNCH1,T2,RR,SNL,WF,PE,SN1
PUNCH1,DW1,BP1,BP2,TP1,TP2,ALP
PUNCH1,DR,WR,TFP,DFP,DS1,ALSH
PUNCH1,P1,P2,P3,P4,P5,P7
PUNCH1, RS,GC,PT,C1,CW,CP
PUNCH1, EL,CM,CQ,DW,CC,PBA
PUNCH1, GE,CS,CF,FS,EC,DF
PUNCH1,ALG3,DC1,DG3,DG2,AL1,AL2
PUNCH1,AL3,ALCO,G2,G3,A.
PUNCH1,HM,SM,AS,AC,ET,EB
PUNCH1,S,FK,FR,RC,RG,RP
PAUSE
END

PASS 3

```
1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
    READ1 ,VA,EE,EP,PN,F,PX
    READ1 ,RPM,PI,PF,CK,POL,DI
    READ1 ,DU,CL,SS,HC,SF,QN
    READ1 ,WL,BK,ZZ,B0,B1,B2
    READ1 ,B3,BS,H0,HX,HY,HZ
    READ1 ,HS,HT,HW,QQ,W,RF
    READ1 ,SC,YY,C,TS,SN,DB
    READ1 ,CE,SH,SD,TT,SK,RB
    READ1 , ALCO,TP,D1,FE,RD,RT
    READ1 ,T2,RR,SNL,WF,PE,SN1
    READ1 ,DW1,BP1,BP2,TP1,TP2,ALP
    READ1 ,DR,WR,TFP,DFP,DS1,ALSH
    READ1 ,P1,P2,P3,P4,P5,P7
    READ1 , RS,GC,PT,C1,CW,CP
    READ1 , EL,CM,CQ,DW,CC,PBA
    READ1 , GE,CS,CF,FS,EC,DF
    READ1 ,ALG3,DC1,DG3,DG2,AL1,AL2
    READ1 ,AL3,ALCO,G2,G3,A
    READ 1,HM,SM,AS,AC,ET,EB
    READ 1,S,FK,FR,RC,RG,RP
    IF(PBA-60.0)105,105,108
    105 IF(CS-0.667)106,106,107
    106 FF=0.25*(6.0*CS-1.0)
    107 FF=0.25*(3.*CS+1.0)
    GO TO 75
    108 IF(CF-0.667)109,109,110
    109 FF=0.05*(24.0*CS-1.0)
```

GO TO 75
 110 FF=0.75
 75 CX=FF/(CF*CF*DF*DF)
 Z=CX*20.0/(PN*QN)
 BT=3.142*D1/QQ-B0
 ZA=BT*BT/(16.0*TS*GC)
 ZB=0.35*BT/TS
 ZC=H0/B0
 ZD=HX*0.333/BS
 ZE=HY/BS
 IF(ZZ-2.0) 76,77,78
 76 PC=Z*(ZE+ZD+ZA+ZB)
 GO TO 82
 77 PC=Z*(ZC+(2.0*HT/(B0+BS))+(HW/BS)+ZD+ZA+ZB)
 GO TO 82
 78 IF(ZZ-4.0) 79,80,81
 79 PC=Z*(ZC+(2.0*HT/(B0+B1))+(2.0*HW/(B1+B2))+(HX*0.333/B2)+ZA+ZB)
 GO TO 82
 80 PC=Z*(ZC+0.62)
 GO TO 82
 81 PC=Z*(ZE+ZD+(0.5*GC/TS)+(0.25*TS/GC)+0.6)
 82 EK=EL/(10.0**((0.103*YY*TS+0.402)))
 IF(D1-8.0) 83,83,84
 83 EK=SQRT(EK)
 84 ZF=.612*LOG(10.0*CS)
 EW=6.28*EK*ZF*(TP**((0.62-(0.228*LOG(ZF))))/(CL*DF*DF))
 87 ZA=3.1416*(D1+HS)/QQ
 IF(ZZ-3.0) 88,89,88
 88 TM=ZA-BS

GO TO 90

89 TM=(3.1416*(D1+2.*HS)/QQ)-B3

90 WI=(TM*QQ*SS*HS+(DU-HC)*3.142*HC*SS)*0.283

IF(WF)445,446,445

446 WF=2.52E-6*(DR**2.5)*ALP*RPI**1.5

445 WC=.321*HI*QQ*AC*SC

PUNCH1,VA,EE,EP,PN,F,PX

PUNCH1,RPI1,PI,PF,CK,POL,D1

PUNCH1,DU,CL,SS,HC,SF,QN

PUNCH1,WL,BK,ZZ,BO,B1,B2

PUNCH1,B3,BS,HO,HX,HY,HZ

PUNCH1,HS,HT,HV,QQ,W,RF

PUNCH1,SC,YY,C,TS,SN,DB

PUNCH1,CE,SH,SD,TT,SK,RB

PUNCH1, ALCO,TP,D1,FE,RD,RT

PUNCH1,T2,RR,SNL,WF,PE,SN1

PUNCH1,DW1,BP1,BP2,TP1,TP2,ALP

PUNCH1,DR,WR,TFP,DFP,DS1,ALSH

PUNCH1,P1,P2,P3,P4,P5,P7

PUNCH1, RS,GC,PT,C1,CW,CP

PUNCH1, EL,CM,CQ,DW,CC,PBA

PUNCH1, GE,CS,CF,FS,EC,DF

PUNCH1,ALG3,DC1,DG3,DG2,AL1,AL2

PUNCH1,AL3,ALCO,G2,G3,A

PUNCH1,HM,SM,AS,AC,ET,EB

PUNCH1,S,FK,FR,RC,RG,RP

PUNCH1,FF,CX,PC,EK,EW,TM

PUNCH1,WI,WC

PAUSE

PASS 4

```
1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
READ1 ,VA,EE,EP,PN,F,PX
READ1 ,RPM,PI,PF,CK,POI,DI
READ1 ,DU,CL,SS,HC,SF,QN
READ1 ,WL,BK,ZZ,BO,B1,B2
READ1 ,B3,BS,HO,HX,HY,HZ
READ1 ,HS,HT,HW,QQ,W,RF
READ1 ,SC,YY,C,TS,SN,DB
READ1 ,CE,SH,SD,TT,SK,RB
READ1 ,ALCO,TP,D1,FE,RD,RT
READ1 ,T2,RR,SNL,WF,PE,SN1
READ1 ,DW1,BP1,BP2,TP1,TP2,ALP
READ1 ,DR,WR,TFP,DFP,DS1,ALSH
READ1 ,P1,P2,P3,P4,P5,P7
READ1 ,RS,GC,PT,C1,CW,CP
READ1 ,EL,CM,CQ,DW,CC,PBA
READ1 ,GE,CS,CF,FS,EC,DF
READ1 ,ALG1,DC1,DG3,DG2,AL1,AL2
READ1 ,ALG3,DC1,DG3,DG2,AL1,AL2
READ1 ,AL3,ALCO,G2,G3,A
READ1 ,HM,SM,AS,AC,ET,EB
READ1 ,S,FK,FR,RC,RG,RP
READ1 ,FF,CX,PC,EK,EW,TM
READ1 ,WI,WC
A2=.7854*DG2*DG2
A3=3.1416*DG3*ALG3
AP=BP2*TP2
IF(P1)401,402,401
```

402 P1=3.19*BP1*TP1/AL1
 401 IF(P2)403,404,403
 404 P2=1.595*(TP1+TP2)*ALP/AL2
 403 IF(P3)405,406,405
 406 P3=3.19*((3.*BP1+BP2)/8.)*ALP/AL3
 405 IF(P4)407,408,407
 408 Z=TP-(BP1+BP2)/2.
 P4=(3.19*ALP/3.1416)*LOG(1.+(BP1+BP2)/Z)
 IF(PX-6.)409,407,407
 409 P4=1.5*p4
 407 IF(P5)410,411,410
 411 P5=(2.505/ALC0)*(DC1**2-DS1**2)/4.
 410 IF(P7)412,413,412
 413 P7=5.01*((DR+DU)/2.)*((DU-DR)/2.)+3.1416*DG2*ALG3
 P7=P7/((DU-DR)/2.)
 412 TG=6.E6*EE/(CW*EC*RPM)
 BT1=TG/(QQ*SM*SS)
 FQ=TG*CP/PX
 BC1=FQ/(2.*HC*SS)
 BG1=TG/(3.1416*D1*CL)
 FG=BG1*GE/.00319
 WQ=(DU-HC)*1.42*HC*SS*(BC1/BK)**2.0*WL
 WT= SM *QQ*SS*HS*0.453*(BT1/BK)**2.0*WL
 132 D2=BG1**2.5*0.000061
 D3=(0.0167*QQ*RPM)**1.65*0.000015147
 IF(TS-0.9)133,133,134
 133 D4=TS**1.285*0.81
 GO TO 137
 134 IF(TS-2.0)135,135,136

135 D4=TS**1.145*0.79
GO TO 137

136 D4=TS**0.79*0.92

137 D7=B0/GC
IF(D7-1.7)138,138,139

138 D5=D7**2.31*0.3
GO TO 144

139 IF(D7-3.0)140,140,141

140 D5=D7**2.0*0.35
GO TO 144

141 IF(D7-5.0)142,142,143

142 D5=D7**1.4*0.625
GO TO 144

143 D5=D7**0.965*1.38

144 D6=10.0** (0.932*C1-1.606)
BA=3.142*D1*CL
WN=D1*D2*D3*D4*D5*D6*BA
PUNCH1,VA,EE,EP,PN,F,PX
PUNCH1,RPM,PI,PF,CK,POL,DI
PUNCH1,DU,CL,SS,HC,SF,QN
PUNCH1,WL,BK,ZZ,B0,B1,B2
PUNCH1,B3,BS,H0,HX,HY,HZ
PUNCH1,HS,HT,HW,QQ,W,RF
PUNCH1,SC,YY,C,TS,SN,DB
PUNCH1,CE,SH,SD,TT,SK,RB
- PUNCH1, ALCO,TP,D1,FE,RD,RT
PUNCH1,T2,RR,SNL,WF,PE,SN1
PUNCH1,DW1,BP1,BP2,TP1,TP2,ALP
PUNCH1,DR,WR,TFP,DFP,DS1,ALSH

PUNCH1, RS,GC,PT,C1,CW,CP
PUNCH1, EL,CM,CQ,DW,CC,PBA
PUNCH1, GE,CS,CF,FS,EC,DF
PUNCH1,ALG3,DC1,DG3,DG2,AL1,AL2
PUNCH1,AL3,ALC0,G2,G3,A
PUNCH1,HM,SM,AS,AC,ET,EB
PUNCH1,S,FK,FR,RC,RG,RP
PUNCH1,FF,CX,PC,EK,EW,TM
PUNCH1,WI,WC,WT,WQ,WN
PUNCH1,TG,FQ,BC1,BT1,BG1,FG
PUNCH1,P1,P2,P3,P4,P5,P7
PUNCH1,PX,ALP,A2,G2,A3,G3
PUNCH1,DU,PT,FK,AS
PUNCH1,HC,AP,HS,DS1,ALSH
PAUSE
END

PASS 5

```
DIMENSION AI(90)

1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
888 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)

K=1

823 READ888,AI(K),AI(K+1),AI(K+2),AI(K+3),AI(K+4),AI(K+5)
      K=K+6
      IF(K>89)823,824,824

824 DO 825 J=1,21
      READ 1,R1,R2,R3,R4,R5,R6
825 PUNCH1,R1,R2,R3,R4,R5,R6
      READ1 ,TG,FQ,BC1,BT1,BG1,FG
      READ1 ,P1,P2,P3,P4,P5,P7
      READ1 ,PX,ALP,A2,G2,A3,G3
      READ1 ,DU,PT,FK,AS
      READ1 ,HC,AP,HS,DS1,ALSH.
      LOAD=1
      COREL=3.1416*(DU-HC)/(4.*PX)
      X=BT1
      NA=1
      K=1
      GO TO 802

806 FT=HS*AT
      X=BC1
      K=2
      NA=1
      GO TO 802

807 FC=COREL*AT
      FS=FT+FC
```

PL=(FG+FS)*(P1+P2+P3+P4)*.002

PLT=FQ+PL/PX

BP=PLT/AP

X=BP

NA=31

K=3

GO TO 802

808 FP=ALP*AT

PL7=.001*P7*(FC+FT+FG+FP)

PG2=PLT*PX/2.+PL7

BG2=PG2/A2

FG2=BG2*G2/.00319

BG3=PG2/A3

FG3=BG3*G3/.00319

PL5=P5*(FG2+2.*(FG+FT+FC)+FG3)*.001

PSH=PG2+PL5

ASH=.7854*DS1*DS1

BSH=PSH/ASH

X=BSH

816 K=4

NA=61

GO TO 802

809 FSH=ALSH*AT

FNL=2.*(FG+FT+FC)+FSH+FG2+FG3

A1NL=FNL/PT

CD=A1NL/AS

EPNL=A1NL*FK

PUNCH1,TG,FQ,BC1,BT1,BG1,FG

PUNCH1,P1,P2,P3,P4,P5,P7

PUNCH1,PX,ALP,A2,G2,A3,G3
PUNCH1,DU,PT,FK,AS,FG2,FG3
PUNCH1,HC,AP,HS,DS1,ALSH,EPNL
PUNCH1,COREL,ASH,FC,FT,BP,BSH
PUNCH1,PL,PLT,BG2,BG3,CD,A1NL
PUNCH1,FNL
PAUSE
802 IF(A1(NA)-X)830,831,831
831 NA=NA+3
835 IF(A1(NA)-X)833,834,834
833 NA=NA+2
GO TO 835
834 AX=A1(NA)
BB1=A1(NA-2)
DC=A1(NA+1)
D=A1(NA-1)
XX= (AX-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
Y=AX-XX*.4343*LOG(DC)
AT=EXP(2.306*(X-Y)/XX)
GO TO (838,839),LOAD
838 GO TO (806,807,808,809,810),K
830 GO TO (836,837),LOAD
836 PRINT 850,
850 FORMAT (17HMACHINE SATURATED)
PAUSE
END

PASS 6

3 FORMAT(9X F12.5,2X F12.5)
1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
870 FORMAT(23X F12.5/)
READ1 ,VA,EE,EP,PN,F,PX
READ1 ,RPM,PI,PF,CK,POL,DI
READ1 ,DU,CL,SS,HC,SF,QN
READ1 ,WL,BK,ZZ,BO,B1,B2
READ1 ,B3,BS,HO,HX,HY,HZ
READ1 ,HS,HT,HW,QQ,W,RF
READ1 ,SC,YY,C,TS,SN,DB
READ1 ,CE,SH,SD,TT,SK,RB
READ1 , ALCO,TP,D1,FE,RD,RT
READ1 ,T2,RR,SNL,WF,PE,SN1
READ1 ,DW1,BP1,BP2,TP1,TP2,ALP
READ1 ,DR,WR,TFP,DFP,DS1,ALSH
READ1 , RS,GC,PT,C1,CW,CP
READ1 , EL,CM,CQ,DW,CC,PBA
READ1 , GE,CS,CF,FS,EC,DF
READ1 ,ALG3,DC1,DG3,DG2,AL1,AL2
READ1 ,AL3,ALCO,G2,G3,A
READ1 ,HM,SM,AS,AC,ET,EB
READ1 ,S,FK,FR,RC,RG,RP
READ1 ,FF,CX,PC,EK,EW,TM
READ1 ,WI,WC,WT,WQ,WN
READ1 ,TG,FQ,BC1,BT1,BG1,FG
READ1 ,P1,P2,P3,P4,P5,P7
READ1 ,PX,ALP,A2,G2,A3,G3
READ1 ,DU,PT,FK,AS,FG2,FG3

READ1 ,HC,AP,HS,DS1,ALSH,EPNL
READ1 ,COREL,ASH,FC,FT,BP,BSH
READ1 ,PL,PLT,BG2,BG3,CD,AINI.
READ1 ,FNL
XR=.0707*A*DF/(BG1*C1)
XL=XR*(PC+EW)
XD=90.*EC*P1*CM*DF/(PX*(2.*FG+FG2+FG3))
XQ=CQ*XD/(CM*C1)
XA=XL+XD
XB=XI+XQ
VR=3.1416*DR*RPM/12.
AGE=GE*(2.*FG+FG2+FG3)/(2.*FG)
PGE=3.19*TP*SS*CP/GE
PEE=P1+P2+P3+P4+P5
XF=(XR*PX/SS)*((C1/CP)**2*PGE*PGE)*1.E-6/(6.28*PEE*(AGE/GE)**2)
XU=XL+XF
XS=.88*XU
XX=XS
XY=XB
XN=.5*(XX+XY)
ALA=6.38*D1/(PX*GE)
IF(W)414,415,414
415 X0=0.
GO TO 422
414 IF(CS-1.)417,418,417
418 AKX=1.
AKX1=1.
GO TO 419
417 AA=(3.*YY/(PN*QN))

AKX=AA-.2.

IF(AA/3.-.667)420,420,421

420 AKX1=.75*AA-.25

GO TO 419

421 AKX1=.75*AA+.25

419 ABL=(AKX/(CF**2))*.07*ALA

X0=AKX*(ABL+PC)/AKX1

X0=XR*(X0+(1.667*(HX+2.*HZ))/(PN*QN*CF**2*DF**2*BS)+.2*EW)

422 TC=SI/(FK

RA=PN*p1*p1*RG/(VA*1000.)

TA=XN/(628.32*F*RA)

T5=XS*TC/XA

T4=2./F

FSC=XA*FG

SCR=FNL/FSC

PRINT3,AC,A,S,XR,HM,XL,RG,XD,RP,XQ,ET,XA,EB,XB,PC,XF,EW,SI,WC,XU

PRINT3,WI,XS,TP,XX,WR,XY,VR,XN,AS,X0,FK,TC,FR,TA,RC,T5,P1,T4

PRINT3,P2,TG,P3,FQ,P4,BG1,P5,BT1,P7,BC1,FSC,FT,SCR,FC

PRINT870,FG

PUNCH1,BO,GC,P1,PN,EP,ET

PUNCH1,EB,SC,C,XB,XD,PF

PUNCH1,EE,XA,RG,WF,WQ,WT

PUNCH1,WN,SNL,POL,RP,FR,FNL

PUNCH1,TG,FQ,BC1,BT1,RG1,FG

PUNCH1,P1,P2,P3,P4,P5,P7

PUNCH1,PX,ALP,A2,G2,A3,G3

PUNCH1,DU,PT,FK,AS,FG2,FG3

PUNCH1,HC,AP,HS,DS1,ALSH,EPNL

PUNCH1,COREL,ASH,FC,FT,BP,BSH

PUNCH1,PL.,PLT,BG2,BG3,CD,A1NL

PAUSE

END

PASS 7

```
DIMENSION GB(4),AE(4),DX(4)
1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
READ1 ,B0,GC,P1,PN,EP,ET
READ1 ,EB,SC,C,XB,XD,PF
READ1 ,EE,XA,RG,WF,WQ,WT
READ1 ,WN,SNL,POL,RP,FR,FNL
READ1 ,TG,FQ,BC1,BT1,BG1,FG
READ1 ,P1,P2,P3,P4,P5,P7
READ1 ,PX,ALP,A2,G2,A3,G3
READ1 ,DU,PT,FK,AS,FG2,FG3
READ1 ,HC,AP,HS,DS1,ALSH,EPNL
READ1 ,COREL,ASH,FC,FT,BP,BSH
READ1 ,PL,PLT,BG2,BG3,CD,A1NL
AXX=B0/GC
IF(AXX-1.)964,965,964
965 AKSC=2.6
GO TO 957
964 IF(AXX-3.75)955,955,956
955 AKSC=10.*.178/((AXX-1.)*.334)
GO TO 957
956 AKSC=10.*.11/((AXX-1.)*.174)
957 XX1=P1*P1*PN
XX3=3.*EP*P1*PF
XX2=(ET+EB)/2.-1.
XX4=AKSC*P1*SC/(C*FG)
GB(1)=1.
GB(2)=1.5
GB(3)=2.
```

```
GB(4)=POL.  
AN=ATAN(SQRT(1.-PF*PF)/PF)  
AN1=SIN(AN)  
DO 777 K=1,4  
YB=GB(K)  
AA =ATAN((AN1+XB*YB/100.)/PF)  
AE(K)=COS(AA-AN)+XA*SIN(AA)*YB/100.  
777 DX(K)=.93*XD*YB*SIN(AA)/100.  
PUNCH1,AE(1),AE(2),AE(3),AE(4)  
PUNCH1,DX(1),DX(2),DX(3),DX(4)  
PUNCH1,B0,GC,P1,PN,EP,ET  
PUNCH1,EB,SC,C,XB,XD,PF  
PUNCH1,EE,XA,RG,WF,WQ,WT  
PUNCH1,VN,SNL,POL,RP,FR,FNL  
PUNCH1,TG,FQ,BC1,BT1,BG1,FG  
PUNCH1,P1,P2,P3,P4,P5,P7  
PUNCH1,PX,ALP,A2,G2,A3,G3  
PUNCH1,DU,PT,FK,AS,FG2,FG3  
PUNCH1,HC,AP,HS,DS1,ALSH,EPNL  
PUNCH1,COREL,ASH,FC,FT,BP,BSH  
PUNCH1,PL,PLT,BG2,BG3,CD,A1NL  
PUNCH1,XX1,XX2,XX3,XX4  
PAUSE  
END
```

PASS 8

```
DIMENSION AI(90)
DIMENSION AE(4),DX(4),BPL(4),PLL(4),BG3L(4),BSHL(4),PTLL(4)
DIMENSION FFL(4),AIFL(4),CDD(4),EPFL(4),BG2L(4)
1 FORMAT(E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)
888 FORMAT(F10.0,F10.0,F10.0,F10.0,F10.0,F10.0)
K=1
823 READ888,AI(K),AI(K+1),AI(K+2),AI(K+3),AI(K+4),AI(K+5)
K=K+6
IF(K>89)823,824,824
824 READ1 ,AE(1),AE(2),AE(3),AE(4)
READ1 ,DX(1),DX(2),DX(3),DX(4)
READ1 ,BO,GC,PI,PN,EP,ET
READ1 ,EB,SC,C,XB,XD,PF
READ1 ,EE,XA,RG,WF,WQ,WT
READ1 ,WN,SNL,POL,RP,FR,FNL
READ1 ,TG,FQ,BG1,BT1,BG1,FG
READ1 ,P1,P2,P3,P4,P5,P7
READ1 ,PX,ALP,A2,G2,A3,G3
READ1 ,DU,PT,FK,AS,FG2,FG3
READ1 ,HC,AP,HS,DS1,ALSH,EPNL
READ1 ,COREL,ASH,FC,FT,BP,BSH
READ1 ,PL,PLT,BG2,BG3,CD,A1NL
READ1 ,XX1,XX2,XX3,XX4
LOAD=2
DO 900 J=1,4
AED=AE(J)
AA=AED*FG+(1.+PF)*FT+FC
PLL(J)=PL*AA /(FG+FT+FC)
```

```

PR      = PLT*(AED-DX(J))
PTLL(J)=PR+PLL(J)
X=PTLL(J)/AP
NA=31
K=1
GO TO 802
841 FPL= AT* ALP
PL7L=P7*.002*(AA+FPL)
PG2L=(PTLL(J)*PX/2.0)+PL7L
BG2L(J)=PG2L/A2
FG2L=BG2L(J)*G2/.00319
BG3L(J)=PG2L/A3
FG3L=BG3L(J)*G3/.00319
PL5L=P5*.001*(2.*AED*FG+FG2L+FG3L+2.*FT*(1.+PF))
PSHL=PG2L+PL5L
X= PSHL/ASH
BSHL(J)=X
NA=61
K=2
GO TO 802
842 FSHL=AISH*AT
FFL(J)=FSHL+FG2L+FG3L+2.*FG*AED+2.*FT*(1.+PF)
AIFL(J)=FFL(J)/PT
CDD(J)=AIFL(J)/AS
900 EPFL(J)=AIFL(J)*FR
837 JA=JA/3
PUNCH 860,JA
860 FORMAT (13)
IF(JA)861,862,861

```

861 DO 863 J=1,JA
PUNCH1,PLL(J),PTLL(J),BSHL(J),BG3L(J),BG2L(J),BPL(J)
863 PUNCH1,FFL(J),AIFL(J),CDD(J),EPFL(J)
862 PUNCH1,B0,GC,P1,PN,EP,ET
PUNCH1,EB,SC,C,XB,XD,PF
PUNCH1,EE,XA,RG,WF,WQ,WT
PUNCH1,WN,SNL,POL,RP,FR,FNL
PUNCH1,TG,FQ,BC1,BT1,BG1,FG
PUNCH1,P1,P2,P3,P4,P5,P7
PUNCH1,PX,ALP,A2,G2,A3,G3
PUNCH1,DU,PT,FK,AS,FG2,FG3
PUNCH1,HC,AP,HS,DS1,ALSH,EPNL
PUNCH1,COREL,ASH,FC,FT,BP,BSH
PUNCH1,PL,PLT,BG2,BG3,CD,A1NL
PUNCH1,XX1,XX2,XX3,XX4
PAUSE
802 IF(AI(NA)-X)830,831,831
831 NA=NA+3
835 IF(AI(NA)-X)833,834,834
833 NA=NA+2
GO TO 835
834 AX=AI(NA)
BB1=AI(NA-2)
DC=AI(NA+1)
D=AI(NA-1)
XX= (AX-BB1)/(.4343*(LOG(DC)-LOG(D+.0001)))
Y=AX-XX*.4343*LOG(DC)
AT=EXP(2.306*(X-Y)/XX)
GO TO (838,839),LOAD

838 GO TO (806,807,808,809,810),K

839 JA=JA+1

GO TO (841,842,843),K

830 GO TO (836,837),LOAD

836 PRINT 850,

850 FORMAT (17H~~MACHINE SATURATED~~)

PAUSE

END

PASS 9

```
DIMENSION WNL(4),STTL(4),SCUL(4),EDDL(4),TOTL(4),PEFF(4),GB(4)
DIMENSION BPL(4),BG2L(4),FFL(4),AIFL(4),CDD(4),EPFL(4),FCUL(4)
DIMENSION PLL(4),PTLL(4),BG3L(4),BSHL(4)

961 FORMAT(F11.3,8X F11.3,F11.3,F11.3,F11.3)

860 FORMAT (13)

1 FORMAT (E11.5,E11.5,E11.5,E11.5,E11.5,E11.5)

DO 705 N=1,4

PLL(N)=0
PTLL(N)=0
BPL(N)=0
BG2L(N)=0
BSHL(N)=0
BG3L(N)=0
FFL(N)=0
AIFL(N)=0
CDD(N)=0
EPFL(N)=0
FCUL(N)=0
WNL(N)=0
STTL(N)=0
SCUL(N)=0
EDDL(N)=0
TOTL(N)=0

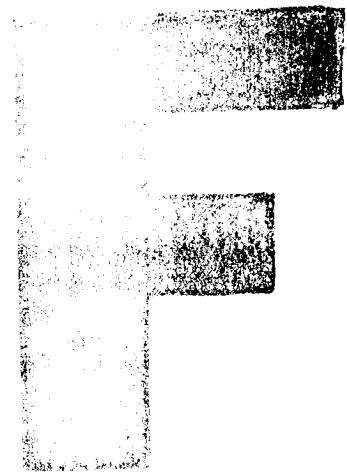
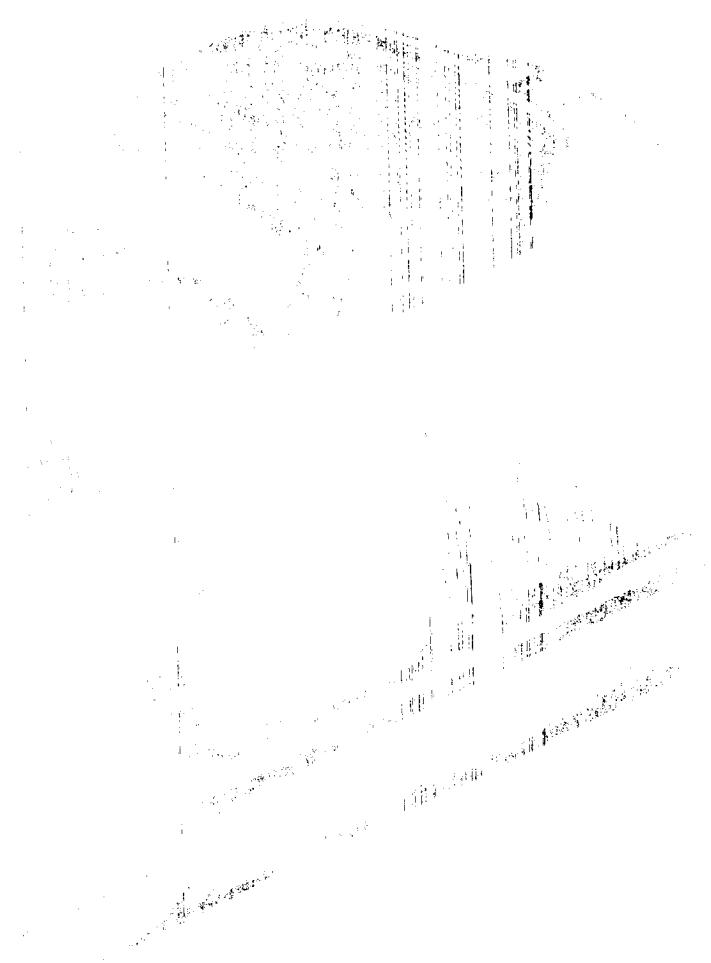
705 PEFF(N)=0
READ860,JA
IF(JA)702,703,702

702 DO 704 J=1,JA
READ1 ,PLL(J),PTLL(J),BSHL(J),BG3L(J),BG2L(J),BPL(J)
```

704 READ1 ,FFL(J),AIFL(J),CDD(J),EPFL(J)
703 READ1 ,R0,GC,PI,PN,EP,ET
READ1 ,EB,SC,C,XB,XD,PF
READ1 ,EE,XA,RG,WF,WQ,WT
READ1 ,WN,SNL,POL,RP,FR,FNL
READ1 ,TG,FQ,BC1,BT1,BG1,FG
READ1 ,P1,P2,P3,P4,P5,P7
READ1 ,PX,ALP,A2,G2,A3,G3
READ1 ,DU,PT,FK,AS,FG2,FG3
READ1 ,HC,AP,HS,DS1,ALSH,EPNL
READ1 ,COREL,ASH,FC,FT,BP,BSH
READ1 ,PL,PLT,BG2,BG3,CD,A1NL
READ1 ,XX1,XX2,XX3,XX4
IF(SNL)707,706,707
707 PUNCG1,TG,FQ,BC1,BT1,BG1,FG
PUNCH1,P1,P2,P3,P4,P5,P7
PUNCH1,PX,ALP,A2,G2,A3,G3
PUNCH1,ASH,COREL,HC,AP,HS,ALSH
PUNCH1,DU,EE
706 FEL=A1NL*A1NL*FK
TL=FEL+WT+WQ+WN+WF
ABX=0
IF(JA)714,712,714
714 IF(JA-4) 708,709,708
709 IF(POL)708,710,708
710 JA=JA-1
708 GB(1)=1.
GB(2)=1.5
GB(3)=2.

```
GB(4)=POL
DO 711 K=1,JA
  YB=GB(K)
  FCUL(K)=AIFL(K)**2*FR
  STTL(K)=((.0027*XA*YB)**2*2.+1.)*WT
  WNL(K)=((XX4*YB)**2+1.)*WN
  SCUL(K)=XX1*RP*YB
  EDDL(K)=SCUL(K)*XX2
  TOTL(K)=EDDL(K)+SCUL(K)+WNL(K)+STTL(K)+FCUL(K)+WQ+WF
711 PEFF(K)=XX3*YB*100./(XX3*YB+TOTL(K))
712 IF(POL)958,959,958
958 PRINT961,PL,PLL(1),PLL(2),PLL(3),PLL(4)
      PRINT961,PLT,PTLL(1),PTLL(2),PTLL(3),PTLL(4)
      PRINT961,BP,BPL(1),BPL(2),BPL(3),BPL(4)
      PRINT961,BG2,BG2L(1),BG2L(2),BG2L(3),BG2L(4)
      PRINT961,BG3,BG3L(1),BG3L(2),BG3L(3),BG3L(4)
      PRINT961,BSH,BSHL(1),BSHL(2),BSHL(3),BSHL(4)
      PRINT961,FNL,FFL(1),FFL(2),FFL(3),FFL(4)
      PRINT961,AINL,AIFL(1),AIFL(2),AIFL(3),AIFL(4)
      PRINT961,CD,CDD(1),CDD(2),CDD(3),CDD(4)
      PRINT961,EPNL,EPFL(1),EPFL(2),EPFL(3),EPFL(4)
      PRINT961,WQ,WQ,WQ,WQ,WQ
      PRINT961,WT,STTL(1),STTL(2),STTL(3),STTL(4)
      PRINT961,ABX,SCUL(1),SCUL(2),SCUL(3),SCUL(4)
      PRINT961,ABX,EDDL(1),EDDL(2),EDDL(3),EDDL(4)
      PRINT961,WN,WNL(1),WNL(2),WNL(3),WNL(4)
      PRINT961,FEL,FCUL(1),FCUL(2),FCUL(3),FCUL(4)
      PRINT961,WF,WF,WF,WF,WF
      PRINT961,TL,TOTL(1),TOTL(2),TOTL(3),TOTL(4)
```

PRINT961,ABX,PEFF(1),PEFF(2),PEFF(3),PEFF(4)
PAUSE
959 PRINT961,PL,PLL(1),PLL(2),PLL(3)
PRINT961,PLT,PTLL(1),PTLL(2),PTLL(3)
PRINT961,BP,BPL(1),BPL(2),BPL(3)
PRINT961,BG2,BG2L(1),BG2L(2),BG2L(3)
PRINT961,BG3,BG3L(1),BG3L(2),BG3L(3)
PRINT961,BSH,BSHL(1),BSHL(2),BSHL(3)
PRINT961,FNL,FFL(1),FFL(2),FFL(3)
PRINT961,AINL,AIFL(1),AIFL(2),AIFL(3)
PRINT961,CD,CDD(1),CDD(2),CDD(3)
PRINT961,EPNL,EPFL(1),EPFL(2),EPFL(3)
PRINT961,WQ,WQ,WQ,WQ
PRINT961,WT,STTL(1),STTL(2),STTL(3)
PRINT961,ABX,SCUL(1),SCUL(2),SCUL(3)
PRINT961,ABX,EDDL(1),EDDL(2),EDDL(3)
PRINT961,WN,WNL(1),WNL(2),WNL(3)
PRINT961,FEL,FCUL(1),FCUL(2),FCUL(3)
PRINT961,WF,WF,WF,WF
PRINT961,TL,TOTL(1),TOTL(2),TOTL(3)
PRINT961,ABX,PEFF(1),PEFF(2),PEFF(3)
PAUSE
END



PERMANENT MAGNET, A.C. GENERATORS

PERMANENT MAGNET, A.C. GENERATOR

INTRODUCTION

In the following section a design procedure for permanent magnet generators is given and explained.

For this quarterly report the procedure is given for hand calculation but is arranged so that the same format can be used in the final report, programmed in Fortran for computer use.

Much of the formulae used in the design procedure is taken from the papers:

"Design Calculations For Permanent Magnet Generators" by David Ginsberg and L. J. Misenheimer, AIEE Trans. 1953 Part III, pp. 96-102.

"Synchronous Machine With Rotating Permanent Magnet Fields, Part II" by Fritz Strauss, AIEE Trans. 1952, Part III, pp. 887-893.

Permanent Magnet, A. C. Generators

Permanent magnet A. C. generators have advantages that make them attractive for use in space power systems when both the P. M. generator limitations and the conversion system limitations are recognized. They have high efficiency, high reliability and are simple.

Against the advantages of high efficiency and high reliability, the P. M. generator is difficult to regulate and its weight is usually greater, in ratings above 5 kva, than the weight of an equivalent electromagnetic generator.

Types of P. M. Generators

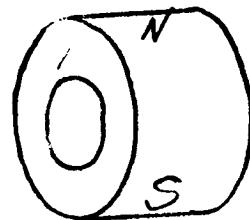
Some of the P. M. generator rotor types are portrayed in Figure I. All of these P. M. generator types are calculated in the same way, except that the flux leakage permeance paths are different for each configuration.

The radial air-gap type with the simple block-type magnets is treated here because it is best known and most often encountered. The same design procedure can be used on any P. M. generator if the designer will estimate or calculate the proper leakage paths for the in-stator and out-stator rotor conditions.

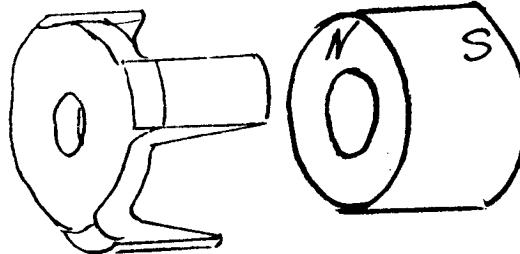
SOME OF THE ROTOR TYPES USED IN A-C

3

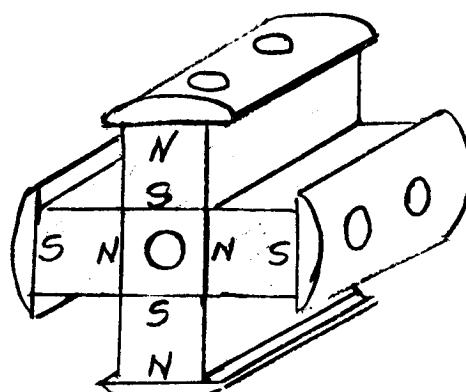
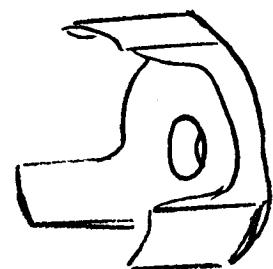
PERMANENT - MAGNET GENERATORS WITH
RADIAL AIR - GAPS



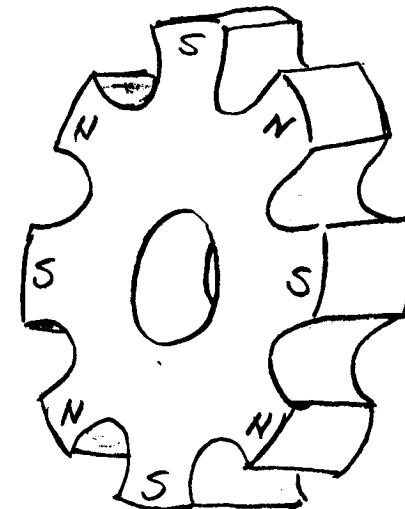
SMOOTH ROTOR



LUNDELL OR CLAW-TYPE ROTOR



BOLTED POLES



CAST POLES

FIGURE I

PERMANENT MAGNET GENERATORS

GENERAL DISCUSSION

One of the first, if not the first, low voltage A.C. generator ever built was a permanent magnet generator built by M. Hyppolyte Pixii and demonstrated before the Paris Academie des Sciences in 1832.*

Figure II is the photograph of a replica of the Pixii machine, which had an axial air gap. Figure III is a patent drawing of a recently developed permanent magnet generator, which also has an axial air gap.

Permanent magnet generators were at first built for demonstration and for amusement, later for telegraph use, for lighting, for telephone ringing and engine ignition.

P.M. Generators built by a man named Frederick H. Holmes were installed in 1857 and 1858 to power arc-lights in lighthouses at Blackwell, South Foreland, and Dungeness, England. These generators operated at 90 rpm and produced about 1.7 kw each. (See History of Electrical Engineering, Part 3, Journal of IEEE, May, 1955, pp. 280-286.)

* The first electric generators were the influence machines (or electrostatic generators.)

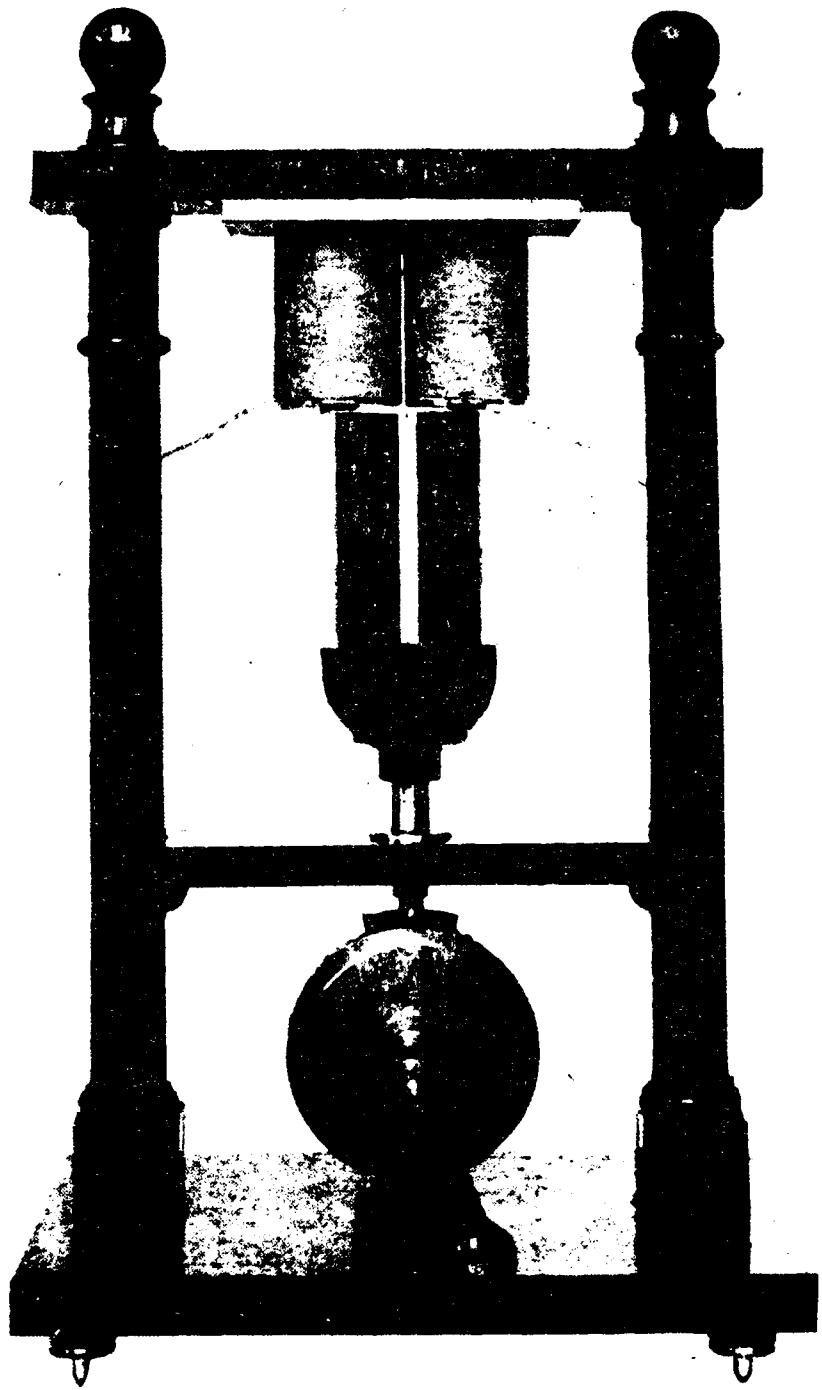
GENERAL DISCUSSION (Contd)

Until 1910, the magnets of the PM generators were almost always made of high carbon steel. Then after 1910, alloy steels began to be used more commonly and magnet performance was improved. Finally, in 1931, a Japanese Metallurgist named Mishima discovered an alloy system of aluminum, nickel, iron, and Cobalt. The alnicos developed from this alloy system have made high performance permanent magnet generators possible.

Table I gives a capsule history of permanent magnets.

One of the strongest magnets commercially available for large size magnets is Alnico 5. It has an energy product of 36000 joules/meter³ or .59 joules/inch³.

The energy product of a magnetic material is the maximum product of flux density B, times the magnetic intensity, H. When B is in Webers/meter² and H is in Ampere-turns/meter, the product is in Joules/meter³. Divide by 61023 and the result is Joules/in³. If Webers/in² and Ampere-turns/inch are multiplied, the result is Joules/in³.



1 *Replica of Pixii hand-driven magneto-electric generator
(about 1832)*

Crown copyright. From an exhibit in the Science Museum,
South Kensington.

Aug. 21, 1962

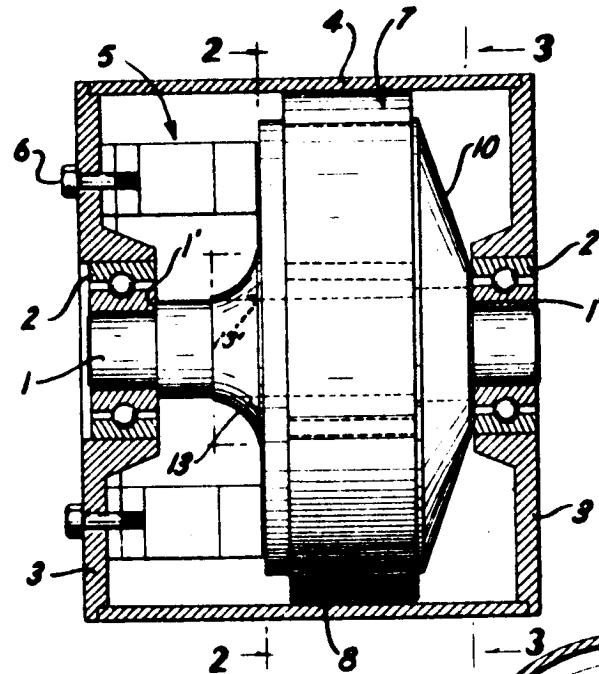
W. KOBER

3,050,648

ROTOR AND METHOD OF ASSEMBLY THEREOF

Filed Jan. 14, 1959

FIG. 1



Having fully disclosed and completely described my invention, and its mode of operation, what I claim as new is:

1. A dynamoelectric rotor comprising, a shaft journaled for rotation about substantially its lengthwise axis, an end plate fixed to said shaft for rotation therewith, a rotor body carrying magnets positioned on said shaft against said end plate, a pole piece structure positioned against the opposite end of said rotor body, and a collar gripping said shaft circumferentially thereof and clamping said pole piece structure and said rotor body against said end plate for rotation therewith.

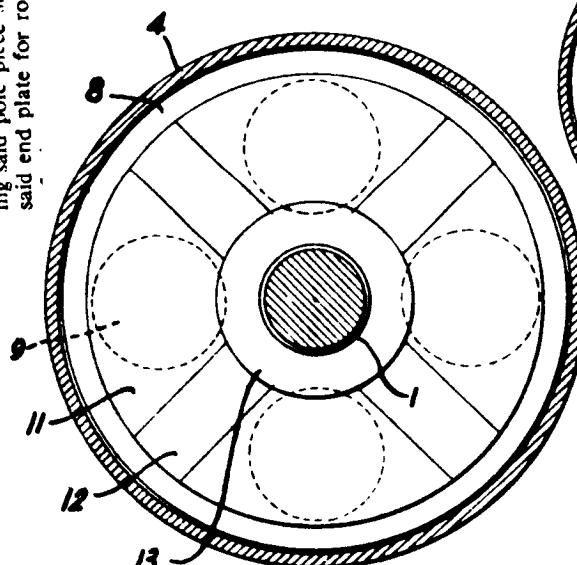


FIG. 2

BY

Bear, Brook, Buckley, Bear
ATTORNEYS

FIGURE

III

INVENTOR.
WILLIAM KOBER

TABLE I

COMPOSITIONS AND PROPERTIES OF
SOME USEFUL PERMANENT MAGNET MATERIALS

Name	When Used	Typical Composition	H _C	B _r	(BH) _m x 10 ³
Tungsten Steel	1885	6 W, 0.7 C, 0.3 Mn	65	10,500	0.3
Low Chrome Steel	1916	0.9 Cr, 0.6 C, 0.4 Mn	50	10,000	0.2
High Chrome Steel	1916	3.5 Cr, 1 C, 0.4 Mn	65	9,500	0.3
KS Magnet Steel	1917	36 Co, 7 W, 3.5 Cr, 0.9 C	230	10,000	0.9
Cobalt Chrome Steel	1921	16 Co, 9 Cr, 1 C, 0.3 Mn	180	8,000	0.6
Remalloy	1931	12 Co, 17 Mo (or W)	250	10,500) 10,000)	1.2) 1.1)
Mishima Alloy	1931	25 Ni, 12 Al	475	7,000	1.4
Alnico 2	1934	12 Co, 17 Ni, 10 Al, 6 Cu	560	7,300	1.7
Magnetoflex	1935	20 Ni, 60 Cu	600	5,800	2.0
Platinum Cobalt Alloy	1936	77 Pt, 23 Co	3000*	5,000	4.5
Vicalloy	1938	52 Co, 10 V	200	11,500	1.5
Alnico 5	1940	24 Co, 14 Ni, 8 Al, 3 Cu	575	12,500	4.5

The maximum energy that a magnet can cause to be stored in an air gap is not the same as the energy product of the magnet. If the air gap permeance corresponds to the maximum BH point on the magnet curve, the energy that can be stored and extracted from the air gap will be the part of the BH rectangle above the air gap line or one-half the energy product of the magnet material.

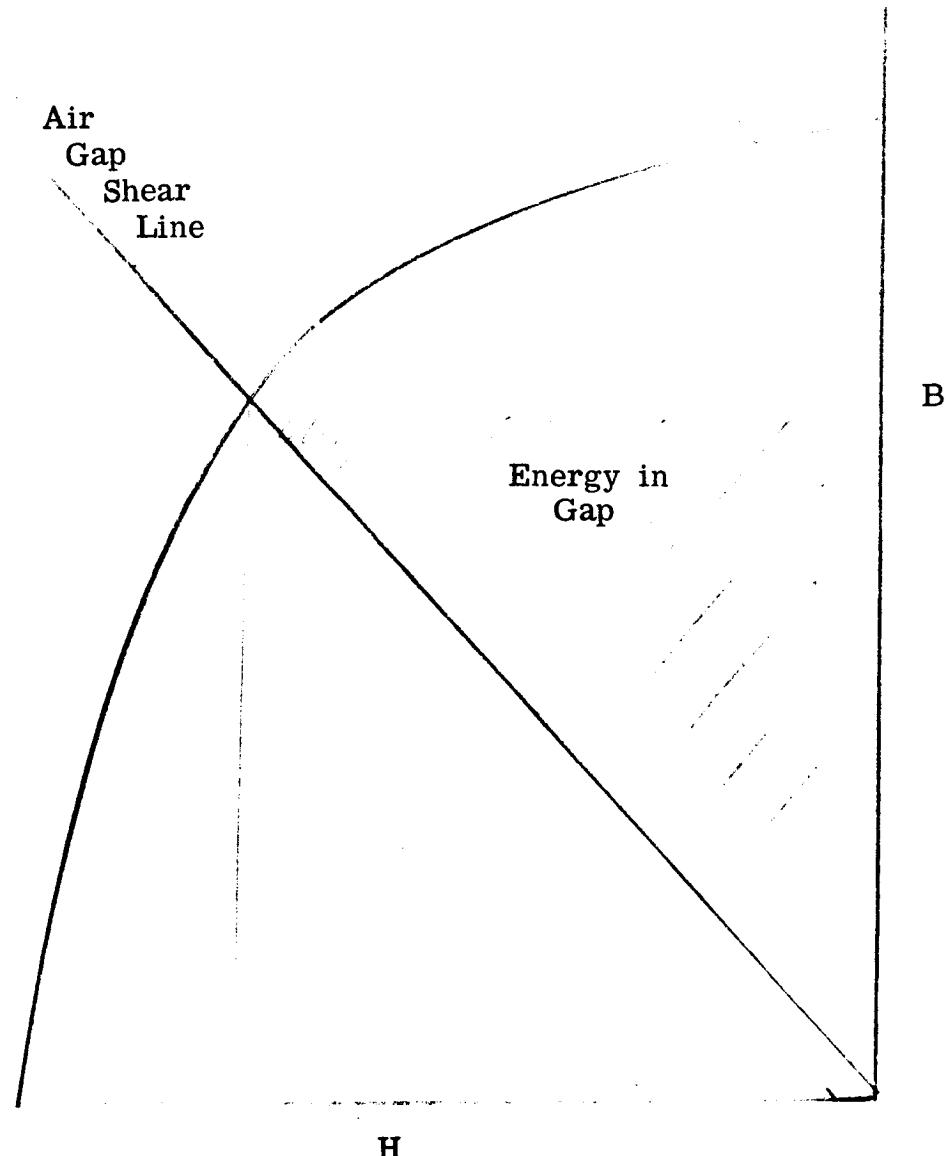


FIGURE IV

How the magnetic energy stored in an air gap of a hard magnetic material is one-half (1/2) the maximum energy product is discussed in the Appendix to this permanent magnet generator design manual.

The following values are given for maximum energy stored in the air gap for various permanent magnets. The Table was taken from Roter's "Electromagnetic Devices." Page 70.

PERMANENT-MAGNET STEELS

TABLE H

Material	Materials Alloyed with Iron	* Incremental Permeability μ_Δ	Maximum Stored Energy of Air Gap $(BdHd)_m$	Flux Density for Max. Energy $\leftarrow B_d$	
		Per Cent	Relative	joules per cu. in.	kmax. per sq. in.
Carbon steel, oil-quenched	0.011	38
Chromium steel	2 Cr, 1C	0.014	41
Chromium steel	6 Cr, 1C	0.022	45
Tungsten steel	5.5 W, 0.7 C	30	0.017	41	
Cobalt-chrome steel	15 Co, 11 Cr, 1C	...	0.040	33	
Cobalt steel	36 Co, 5W, 2 Cr, 0.8 C	9	0.052	35	
Alnico I	12 Al, 20 Ni, 5 Co	6.7	0.091	30	
Alnico II	10 Al, 6 Cu, 17 Ni, 12.5 Co	6.2	0.104	29	
Alnico III (sintered)	10 Al, 6 Cu, 17 Ni, 12.5 Co	...	0.089	28	
Alnico III	12 Al, 25 Ni	6.0	0.085	29	
Alnico IV	12 Al, 28 Ni, 5 Co	3.4	0.085	19	
Alnico V	8 Al, 3 Cu, 14 Ni, 24 Co	3.1	0.286	62	
Nipernmag	12 Al, 32 Ni, + Ti	...	0.087	20	
Platinum-cobalt alloy	77 Pt, 23 Co, 0 Fe	1.1	0.244	16	

PERMANENT-MAGNET STEELS

TABLE

Material	Materials Alloyed with Iron	Resistivity		Specific Gravity	Density
		ρ	δ		
		Per Cent	microhm, inches	lb. per cu. in.	
Carbon steel, oil-quenched	.....	.....	.....	7.82	0.282
Chromium steel	2 Cr, 1C	.....	.....	.....	.....
Chromium steel	6 Cr, 1C	.....	.....	.....	.....
Tungsten steel	5.5 W, 0.7 C	11.8	8.17	8.17	0.295
Cobalt-chrome steel	15 Co, 11 Cr, 1C	.....	.....	.....	.....
Cobalt steel	36 Co, 5W, 2 Cr, 0.8 C	.....	.....	8.27	0.298
Alnico I	12 Al, 20 Ni, 5 Co	.....	.....	31.5	6.9
Alnico II	10 Al, 6 Cu, 17 Ni, 12.5 Co	.....	.....	24.4	7.1
Alnico II (sintered)	10 Al, 6 Cu, 17 Ni, 12.5 Co	.....	.....	.....	.....
Alnico III	12 Al, 25 Ni	25.6	6.9	6.9	0.250
Alnico IV	12 Al, 28 Ni, 5 Co	29.5	7.0	7.0	0.254
Alnico V	8 Al, 3 Cu, 14 Ni, 24 Co	18.5	7.3	7.3	0.264
Nipermag	12 Al, 32 Ni, + Ti	26.0	7.0	7.0	0.254
Platinum-cobalt alloy	77 Pt, 23 Co, 0 Fe	19.7	14.6	14.6	0.529

PERMANENT MAGNET GENERATORS

DESCRIPTION OF PM GENERATOR OPERATION

Permanent Magnets

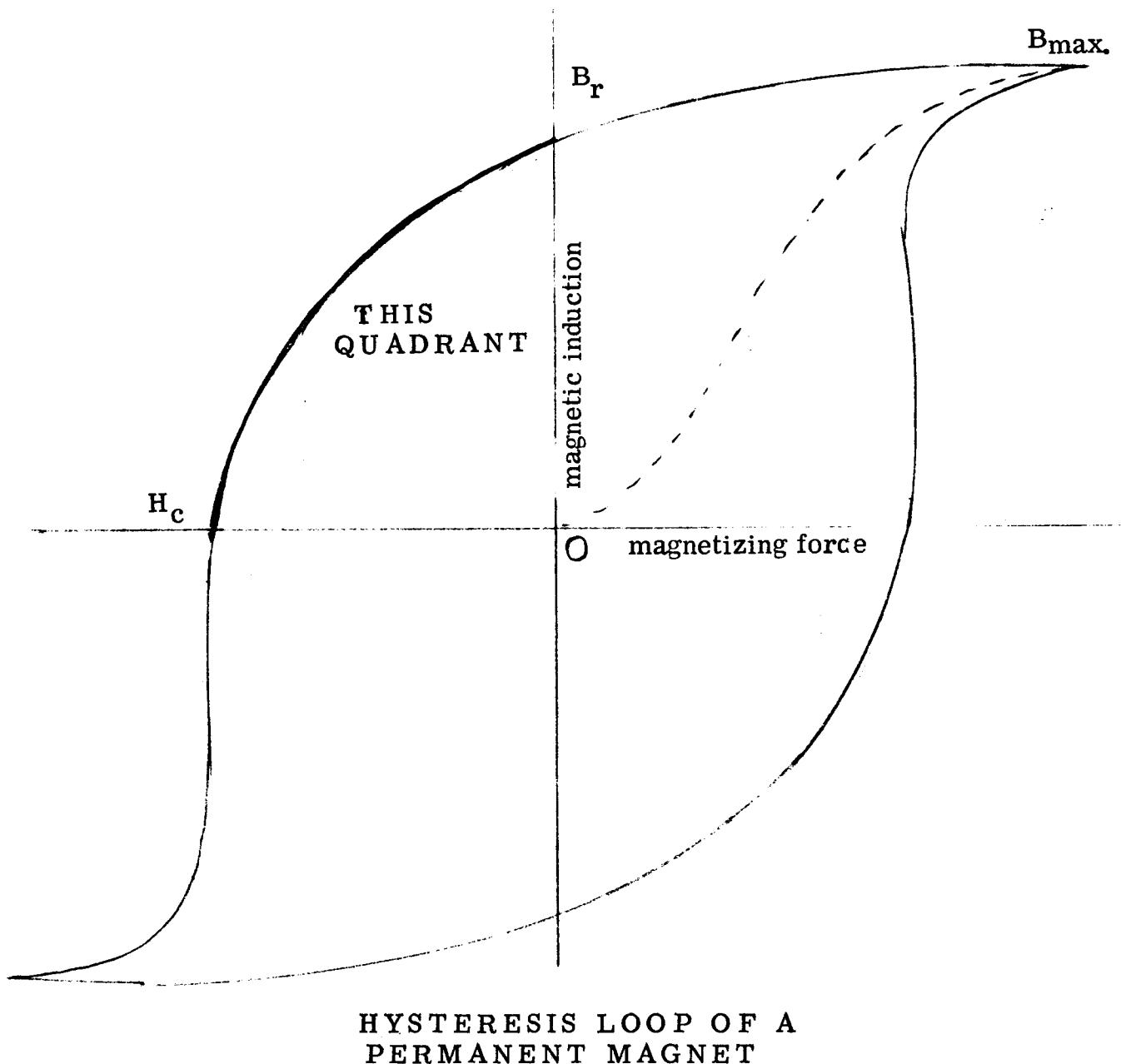
All permanent magnets resist changes in their magnetic state. It is this property that makes the permanent magnet useful.

Most early-day permanent magnets were made of high carbon steel in hard condition. This high carbon steel was used in magnets for magnetos in engine ignition systems, in telephone ringers, toys, etc. It is still used in some applications.

Newer permanent magnets are alloys of nickel, aluminum, Cobalt, copper and iron. The alloy system is called Alnico and magnets made from these alloys are so much stronger than other commercial magnet alloys, that high performance PM generators almost always use them.

A ceramic permanent magnet material is sometimes used for generators when low-cost or high coercive force is of primary importance. The ceramic magnets are used mostly on small d. c. generators and are not of interest for this study.

All good permanent magnet materials have large hysteresis loops and in designing permanent magnet generators one quadrant of the hysteresis loop is used to predict performance.



If a toroid or closed annular ring of permanent magnet steel is excited to its saturation value and then the exciting mmf is removed, the flux density will decrease from the maximum saturation induction value B_{max} to the residual induction B_r . For the flux density in the ring to stabilize at the value B_r , there must be no air gap in the toroid or closed magnetic circuit. If the magnet material is Alnico 5, the flux density in the ring under these conditions will be 78,000 lines per square inch.

If an air gap is introduced in the toroid, the ampere turns required to send flux across the air gap must be supplied by the magnet and this causes the magnet flux density to decrease, still along the hysteresis loop, to some lower value. The actual value depends upon the length of the air gap and upon the length of the magnet.

Think of the magnet as furnishing a certain number of ampere-turns of mmf per inch of magnet. Then when an air gap is introduced into the magnetic circuit, each inch of magnet will contribute its portion of the mmf required to force flux across the air gap.

If an air gap of .010 inches length is introduced in a magnet toroid having a magnet length of ten (10) inches, each inch of magnet will contribute 24 ampere turns toward forcing 77 Kilolines/in² across the gap. Ignore fringing!

$$\text{mmf} = B_g \frac{lg}{u} = 77000 \frac{(.010)}{3.19} = 241 \text{ AT}$$

The magnet AT/inch = $\frac{241}{10} = 24$ and the demagnetizing effect on the magnet is negligible.

If the air gap length is .100" and the magnet length is 10 inches, the mmf required is only 241 ampere-turns per inch of magnet and the demagnetizing effect is still negligible. If, however, the air gap is .100 inches and the magnet length is only 1.0", the ampere-turns required for the one inch of magnet to force 77 K_L across the gap is 2410 which is two times the ampere-turns needed to demagnetize the Alnico 5 magnet completely.

What actually happens in the case of a 1.0" magnet and a 0.100" air gap is that the magnet demagnetizes to a point on the hysteresis curve where the mmf available will force the now lower flux density across the gap. For Alnico 5, the magnet density will be 37 K_L/in² and the mmf/inch = 1200 AT.

In the case of a 1.0" magnet and .100" gap, if the gap is later closed, the magnet density will increase along a minor hysteresis loop having the same slope as the main loop and in this example the magnet density will be 45 K_L/in² when the gap is completely closed.

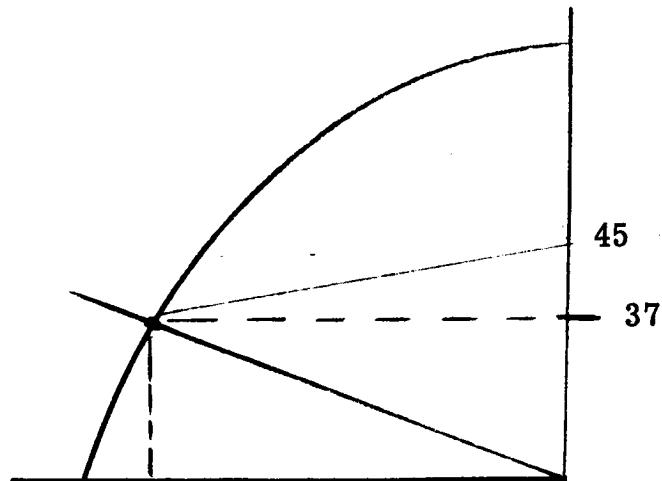
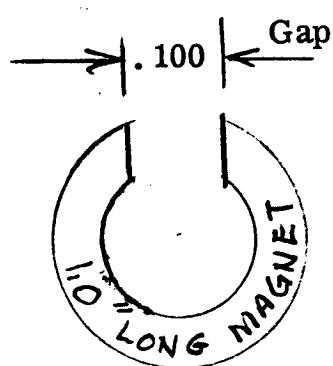
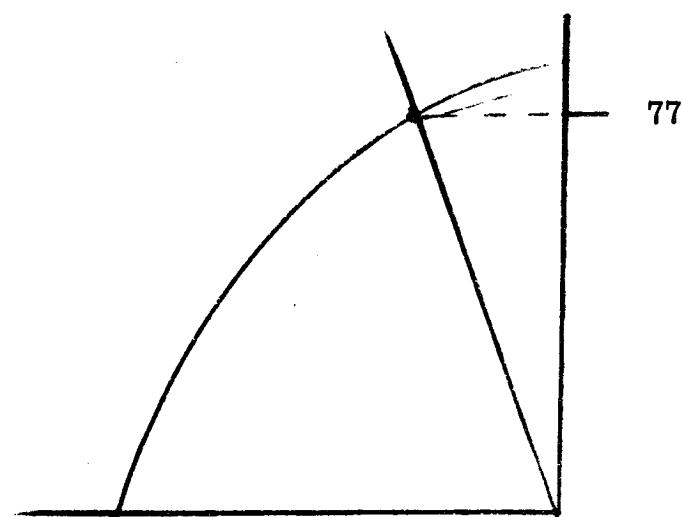
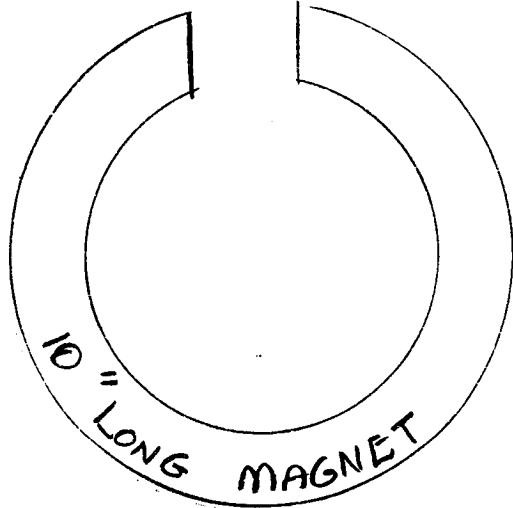
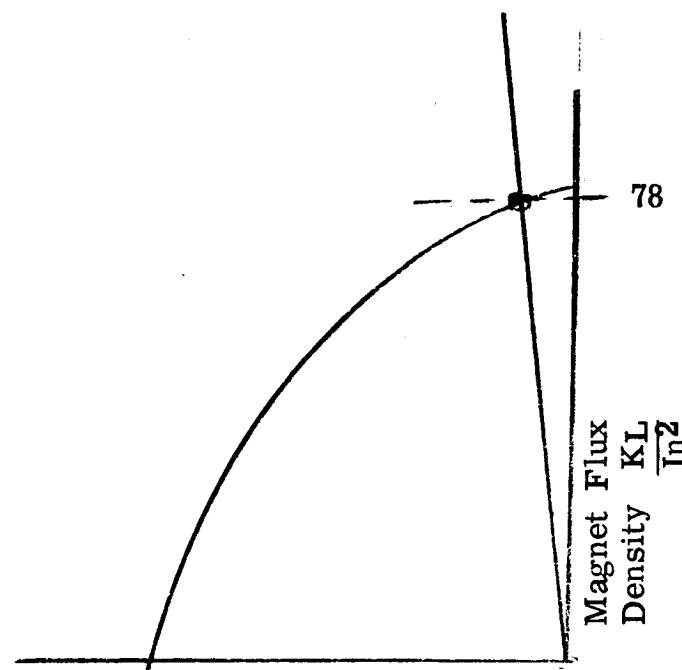
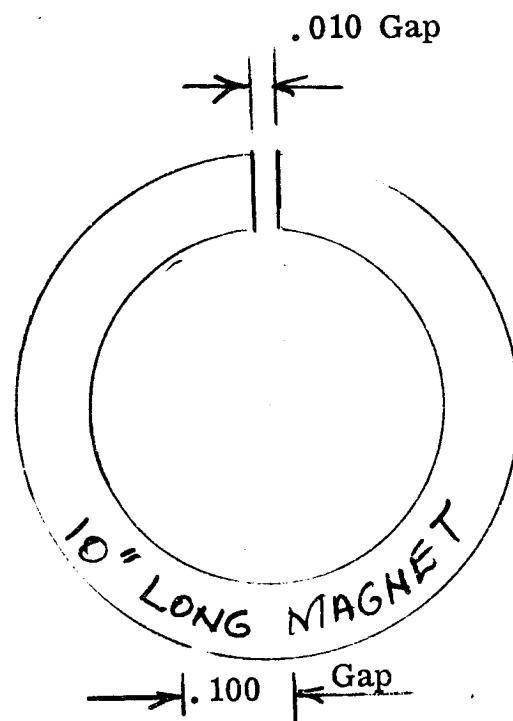


FIGURE VI

When a permanent magnet rotor is constructed and magnetized, then taken out of the magnetizing fixture without a keeper or metal piece to close the magnetic circuit, the magnet density drops to some low value similar to the 1.0" long magnet with .100" air gap. The magnet rotor is said to be air stabilized and the flux circuit is through leakage paths in the air. If the leakage is high enough, the magnet density will remain fairly high. If there were no leakage, the magnet would demagnetize almost completely.

When the air stabilized magnet is placed in a stator, the air gap is partially closed and the magnet density increases along the minor hysteresis loop to a new value that depends on the length of the new air gap. From this time on, the permanent magnet operates along the same minor hysteresis loop unless the demagnetizing ampere-turns of the stator produced by the load on the stator become too great and further demagnetize the magnet. If the armature reaction due to the load does demagnetize the magnet further, the machine is said to be load stabilized and if short circuits are repeatedly applied to the output leads, the magnets are said to be short circuit stabilized.

All permanent magnet materials have large hysteresis loops and, in general, those permanent magnet materials having the largest hysteresis loops are the most useful.

When a magnet is properly applied and stabilized, the level of maximum flux is fixed and the magnet mmf is fixed. To change the voltage generated in a permanent magnet generator for a given load condition, it is customary to change the permeance of the flux path so that less flux flows through the output windings and less voltage is generated.

When no controls are applied to a P.M. generator, the voltage current characteristics curve looks like this:

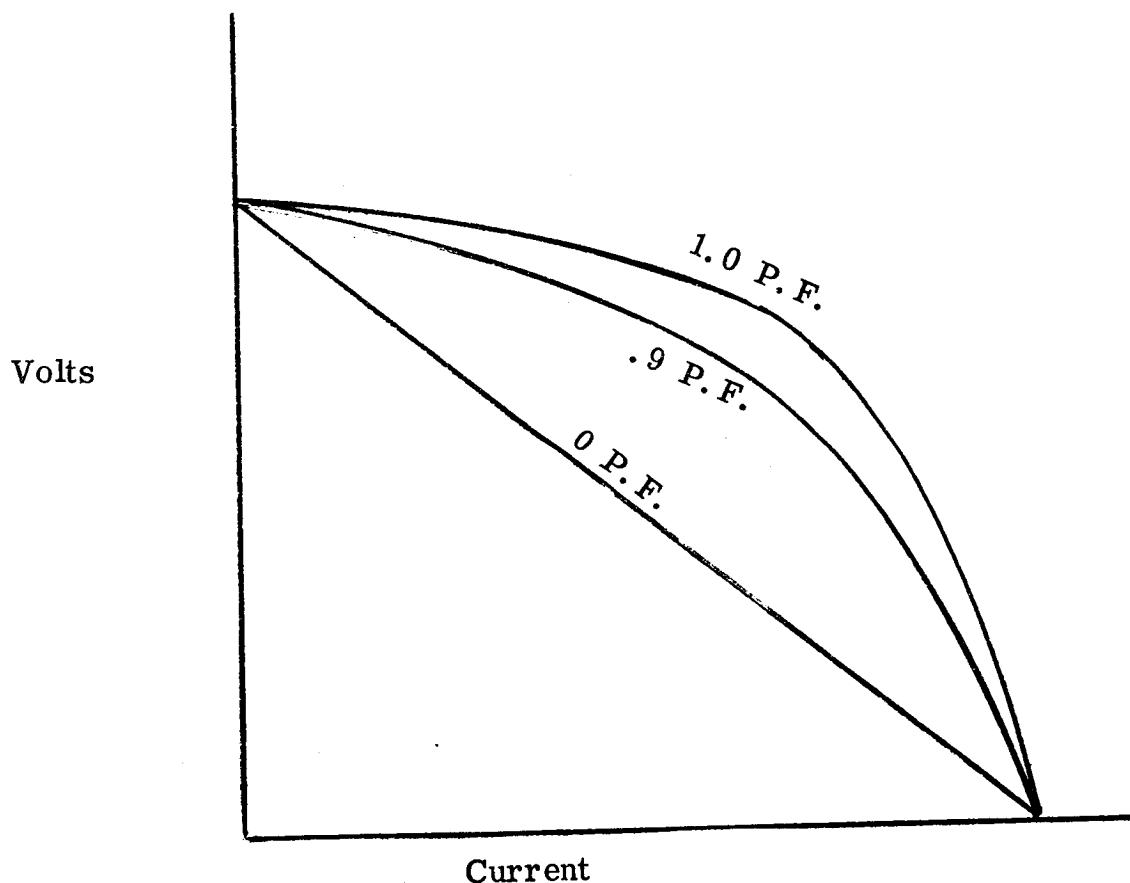


FIGURE VII

If a permanent magnet generator is required to produce a constant voltage from no load to full load, at a fixed speed, the no load voltage is usually depressed by saturating part of the iron circuit so that less flux links the output winding at no load.

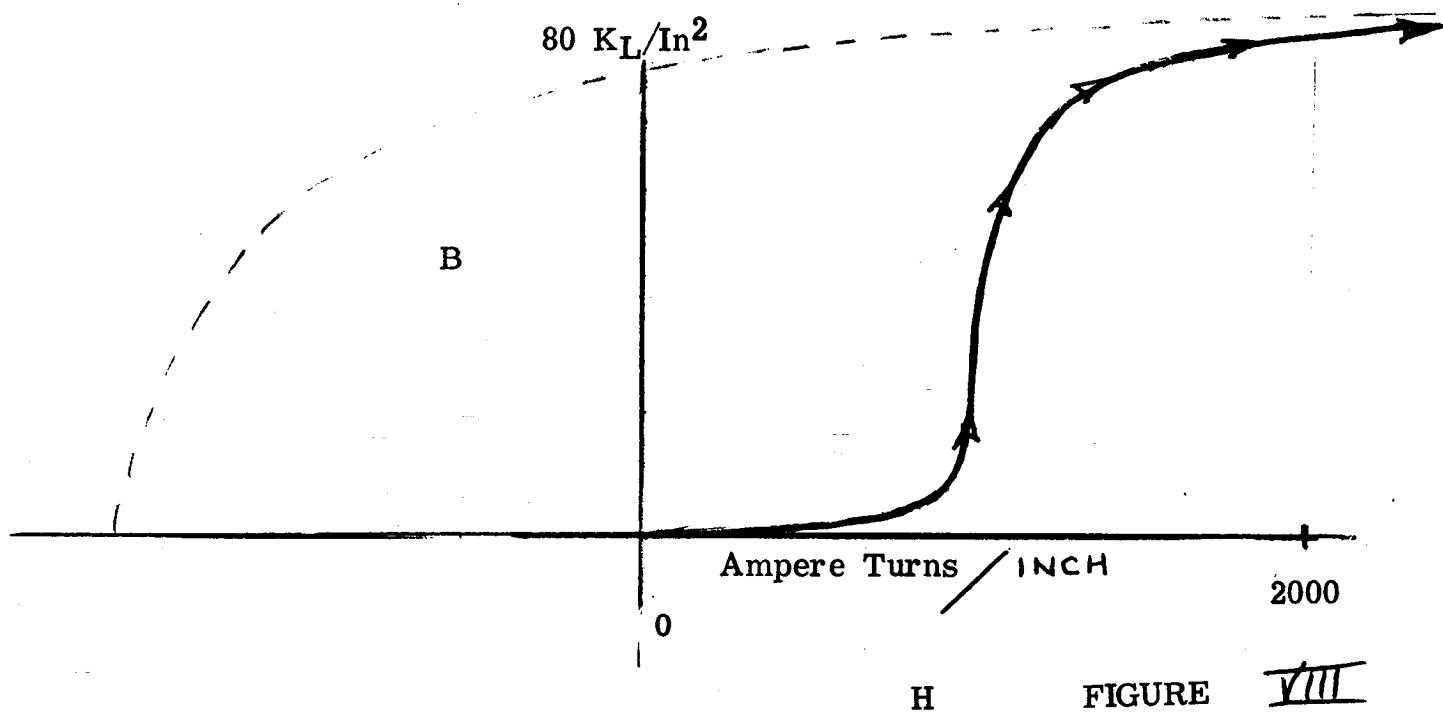
One widely used method of saturating part of the iron circuit is called back-iron control or back-iron saturation and U. S. Patent No. 2564320 issued to N. W. Brainard describes this scheme. Voltage control by this method is usually limited to 10 or 15% of maximum.

Another control method varies the air gap length. In radial gap machines, the rotor is sometimes tapered and designed so that it can be moved axially to increase or decrease the air gap length and the flux linkages in the winding.

U. S. Patent No. 2861238 issued to W. Kober describes a mechanism for adjusting the air gap of an axial gap permanent magnet generator. By adjusting the length of the air gap, the no load voltage can be varied from its maximum to nearly any desired lower level. The air gap control method is effective though relatively slow in response.

When magnets are attached to a rotor and magnetized in a fixture, the magnetic material is subjected to a high magnetomotive force

(mmf) or a high number of ampere turns per inch of magnet. About 4000 ampere-turns per inch are applied to Alnico 5 magnets and the Alnico saturates from zero flux along a saturation curve that looks like this:



H

FIGURE

VIII

As the current in the magnetizer coil is reduced to zero, the flux in the magnet reduces along a hysteresis loop to a residual value B_r .

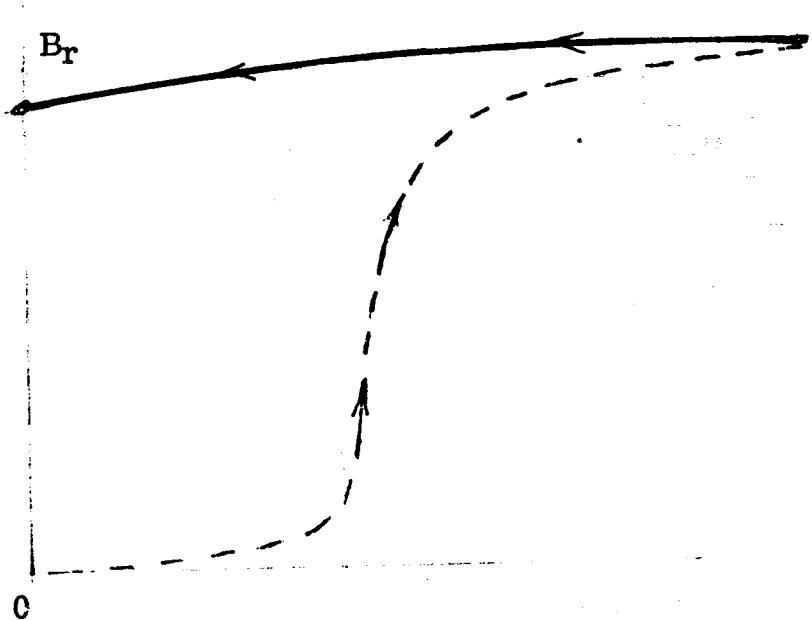


FIGURE IX

As long as the magnet or magnets are in a closed, iron circuit such as the magnetizer or a Keeper, the flux density in the magnet will remain at the value B_r . The magnet is not useable under a closed-circuit condition and an air-gap must be introduced in order to use the magnet.

If the rotor is inserted in a wound stator, and a keeper is kept on the magnets until the magnets are in the stator, the air gap and additional permeance that is introduced will be minimal.

The flux density in the magnet may have dropped to a value about like this:

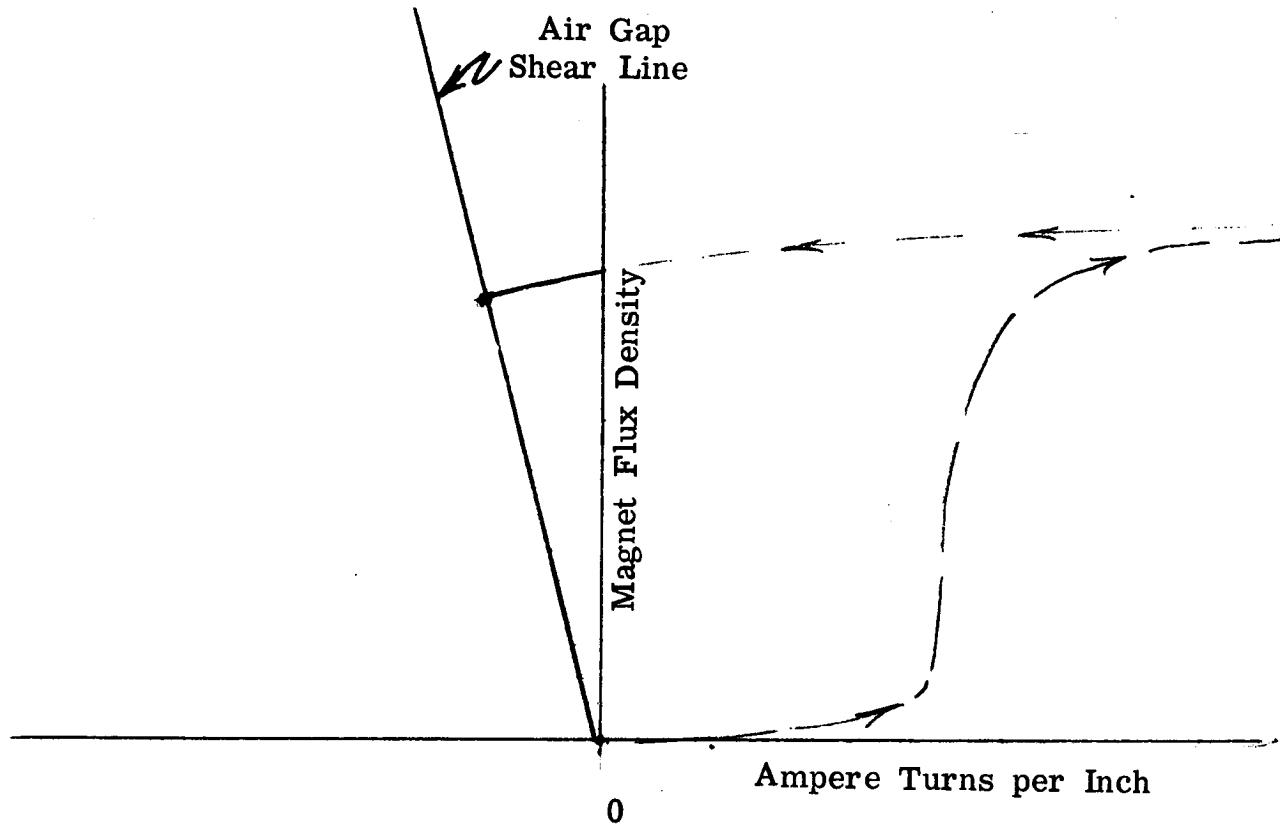


FIGURE X

The flux in the circuit is now at its maximum useable level.

When load is applied, the demagnetizing ampere-turns from the stator oppose the mmf of the magnet and the effect is the same as if the air gap line were shifted over an amount equal to the stator demagnetizing mmf (as related to the magnets per inch.)

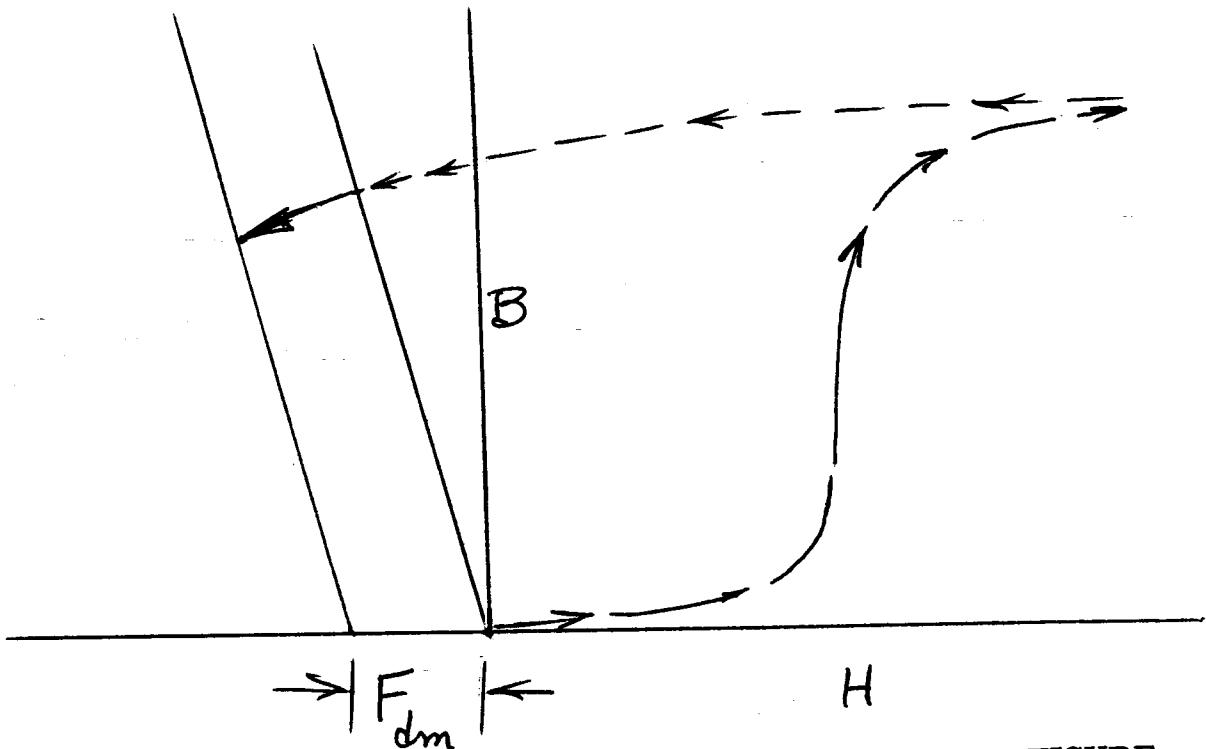


FIGURE XI

Under the stated conditions, the flux density in the magnet never returns to the value it had before load was applied. The flux density returns to a slightly lower value, along a minor hysteresis loop and the generator can be said to be load stabilized. Some tachometers are treated this way and sometimes a larger PM generator for a special application is so treated.

If a short-circuit is applied to the generator, it experiences the maximum demagnetizing force that is possible except for transient demagnetizing forces or external demagnetizing forces. If repeated short circuits are applied by switching them on and off, the

magnets are subjected to many transient demagnetizing mmf's and the magnets are probably stable for most of the possible conditions of loading. The generator is said to be short circuit stabilized. The flux density in the magnets does this:

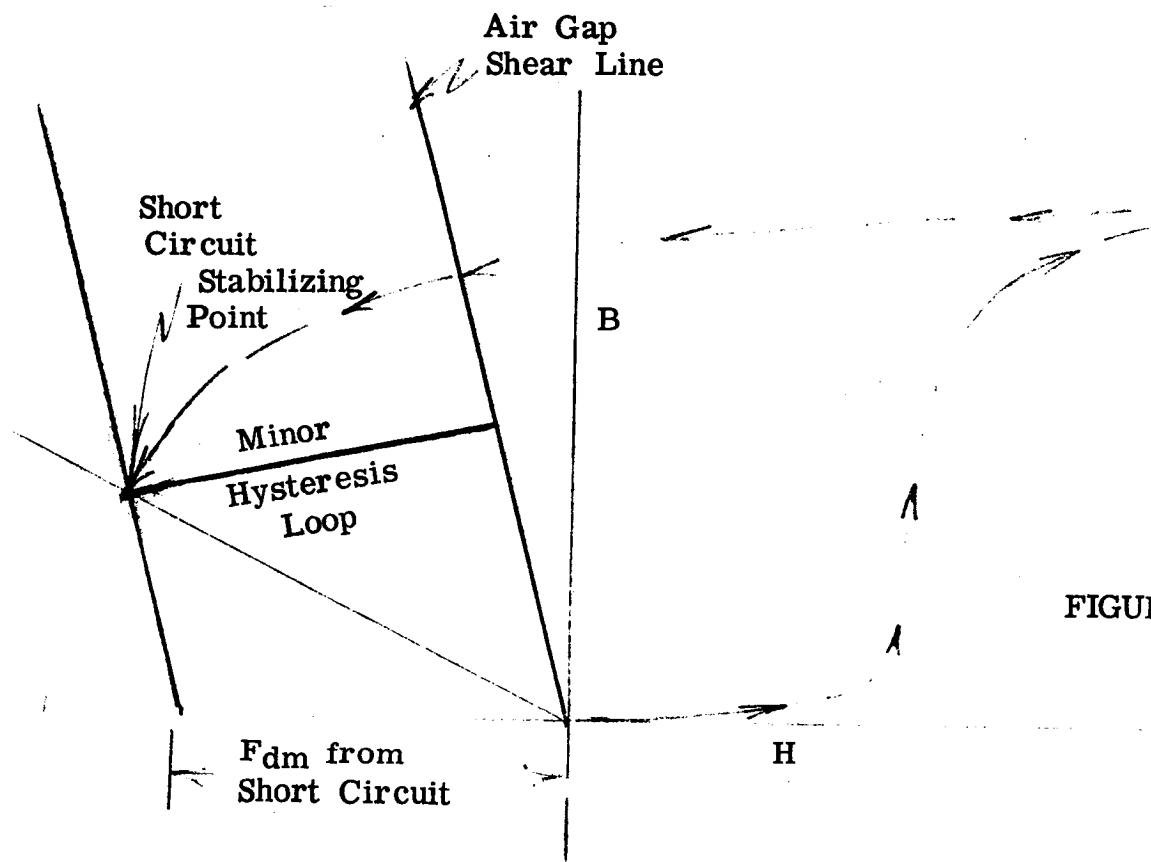


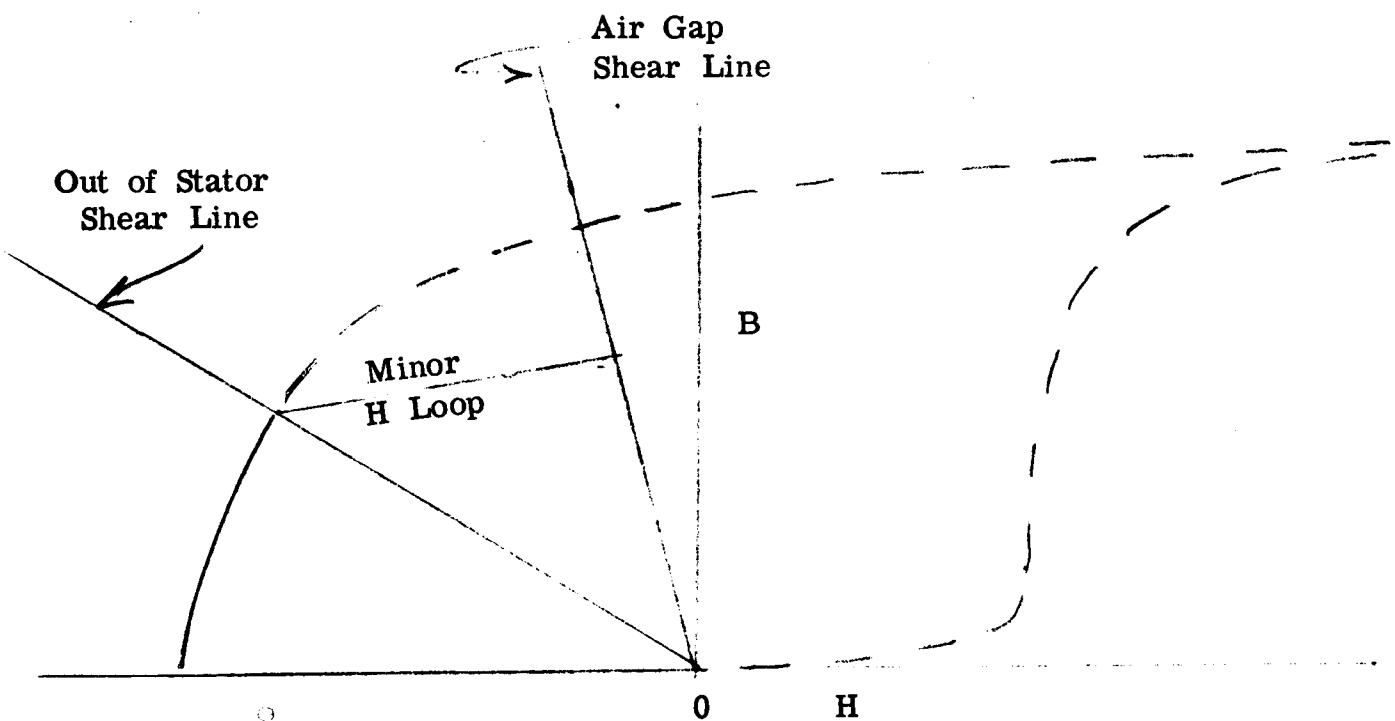
FIGURE XII

If no other severe disturbance affects the magnet adversely, the flux in the magnet will always be a value on the minor hysteresis loop between the air-gap line (at no load) and the short circuit line.

A generator can be designed so that short circuit will demagnetize the magnets almost completely. Then the transients normally associated with testing may cause the magnets to demagnetize beyond their useable strength. When that happens, the rotor must be remagnetized.

If the rotor is taken from the magnetizing fixture without a keeper on it, the circuit for the magnet flux is through the air and, in effect, a huge air gap has been introduced into the circuit. The air gap is the leakage path of the magnets when the rotor is out of the generator stator. This is called air stabilization of the rotor and the permeance of the leakage path air gap is called out-of-stator permeance.

The magnet flux density is represented like this:



FIGURE

XIII

Right here now we will define the permeance terms that are used from here on, even though they are defined later.

Out-stator or Out-of-stator Permeance - This is the permeance of the pole-to-pole flux when the rotor is in air. All of the flux paths are in air and all of the flux is leakage flux since no stator or output winding is present to utilize the magnet flux. The symbol is P_o .

In-Stator Permeance - When the rotor is placed in the stator, some of the flux enters the stator to link the output winding and this is the flux that becomes useful flux.

Some flux still leaks from pole-to-pole and can never be utilized. The permeance path for the never-to-be-utilized leakage flux that is leaking from pole to pole when the rotor is inserted in the stator is called In-stator permeance. It is a leakage permeance and whenever you see the words in-stator permeance in this document they mean the permeance of the in-stator leakage paths of the rotor.

The symbol is P_i .

Air-gap Permeance - The permeance of the air-gap. The symbol is P_g .

Working Air-gap Permeance - The total apparent permeance of the working air-gap. It is the sum of the permeances of the air-gap and the in-stator leakage flux paths. The symbol is P_w .

Magnet Spatial Permeance - This is the adjustment factor to convert the permeance values to the proper scale for use in the conventional hysteresis loop representation. The symbol is P_m .

NOTE --- In the illustrative drawings showing the permeance shear lines, the air-gap shear line is the air-gap permeance plus the in-stator leakage permeance or P_w .

If no further adverse operating conditions are imposed on the magnet, the flux density in the magnet will always be a value on the minor hysteresis loop shown, between the out-stator leakage line and the air gap line.

When the rotor is inserted in the stator, the path for the magnet flux includes the leakage paths between the rotor magnets and around the ends of the magnets. This permeance path is called the in-stator permeance and is lower than the out-of-stator permeance.

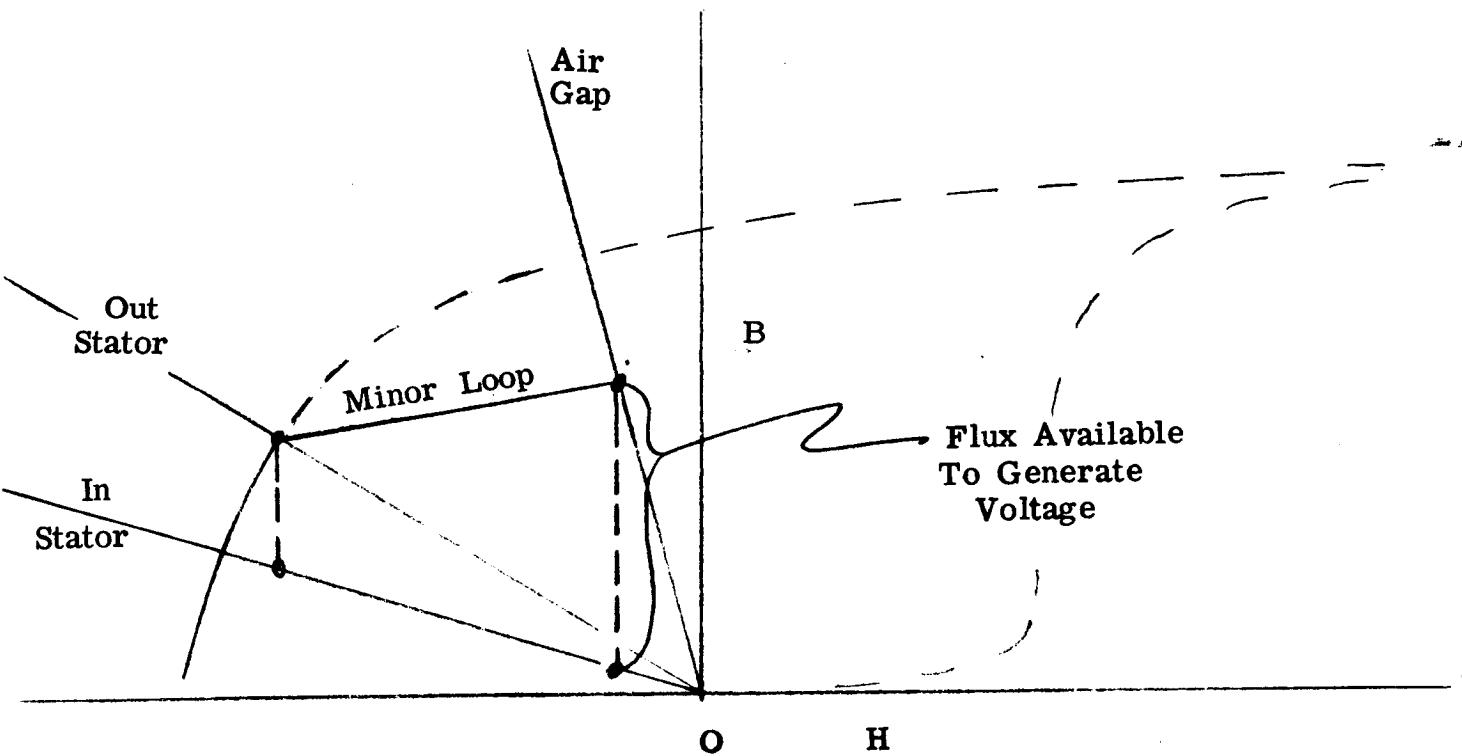


FIGURE XIV

The in-stator permeance is the out-stator permeance minus a few leakage paths. Some out-stator leakage paths no longer exist when the rotor is in the stator because the stator iron completes the flux circuit.

The out-stator permeance establishes the minimum flux level in the magnet and the in-stator permeance establishes the leakage flux level.

The difference between the in-stator flux, which is all leakage, and the maximum flux level determined by the minor hysteresis loop and the air-gap line, gives the value of useful magnet flux that is available to generate voltage.

At zero P.F., as the permanent magnet generator is loaded, the de-magnetizing mmf has the effect of shifting the air-gap line over and the flux available to generate voltage is decreased.

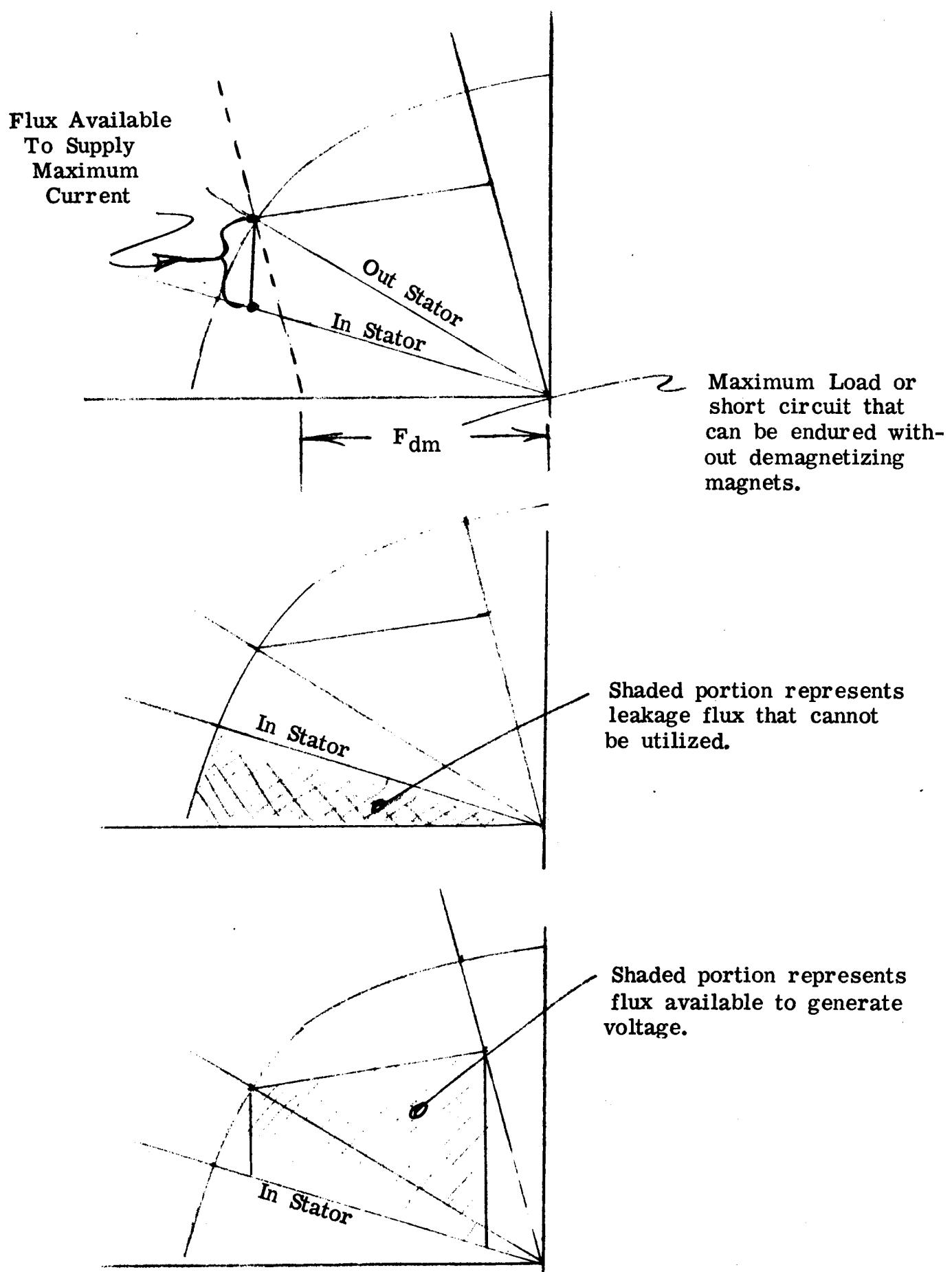
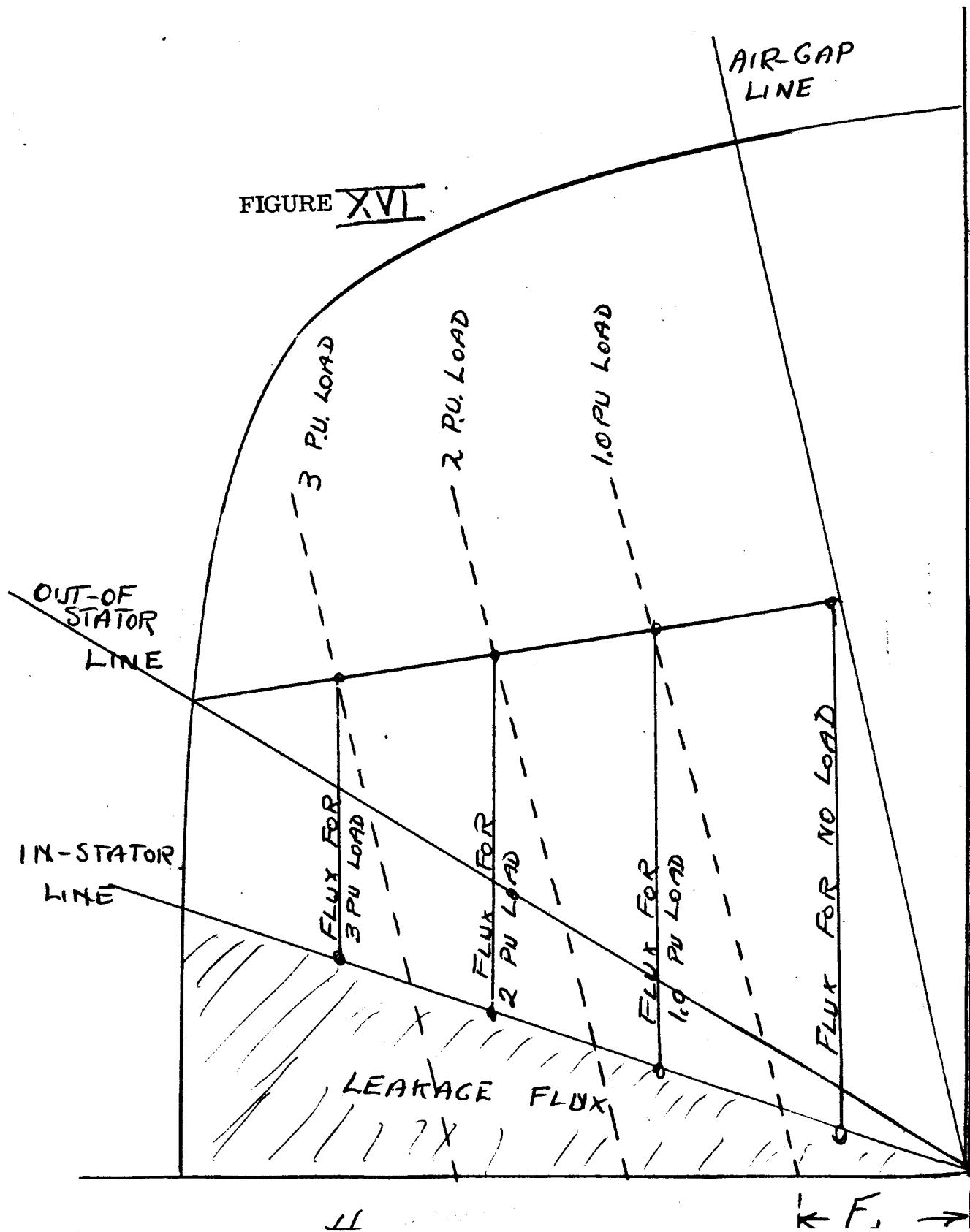


FIGURE XV

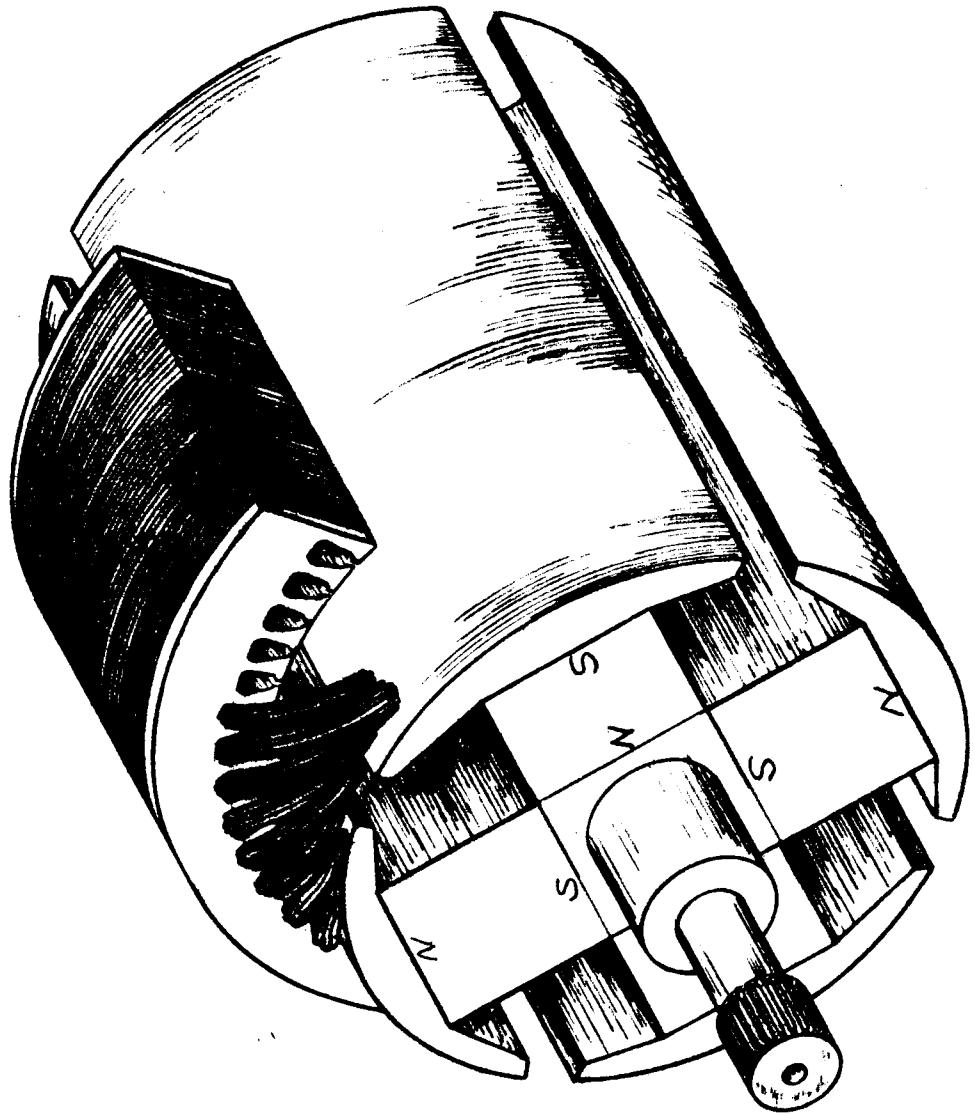
The IZ drop in the windings must be subtracted from the generated voltage and the remaining voltage is the load voltage.



**DESIGN MANUAL
FOR
PERMANENT MAGNET, A.C. GENERATORS**

INTRODUCTION

The calculation procedure given here is for only one configuration of permanent magnet generators. It is the classical design with definite poles consisting of blocks of magnet material. The pole heads are designed to support the magnets and are usually wider than the magnet blocks. Sometimes the pole heads are designed to provide high out-of-stator flux leakage and thereby cause the magnet material to stay magnetized at a high level of flux density even when air-stabilized.



PERMANENT MAGNET GENERATOR

The following sketch illustrates the leakage fluxes that are calculated in determining the performance of the permanent magnet generators covered by this design manual. The formulae and the designations for the permeance calculations are taken from Strauss "Synchronous Machines with Rotating Permanent Magnet Fields" Trans. AIEE 1952 Part II, pp. 887-893. Formulae from Roter's "Electromagnetic Devices" a Wiley and Sons book, are appended to this PM generator design manual and are for use in estimating permeances for configurations of PM generators different from the one discussed in this manual.

When the rotor is magnetized and then removed from the magnetizing fixture without a keeper, the magnet flux density will decrease to a value determined by the out-of-stator leakage permeance. This leakage permeance consists of all of the flux leakage permeances of the rotor when the rotor is out of the stator.

When the rotor is placed in position in the stator, some of the flux that leaked from pole-to-pole when the rotor was by itself, now becomes useful flux by flowing through the stator iron and linking the conductors in the output winding.

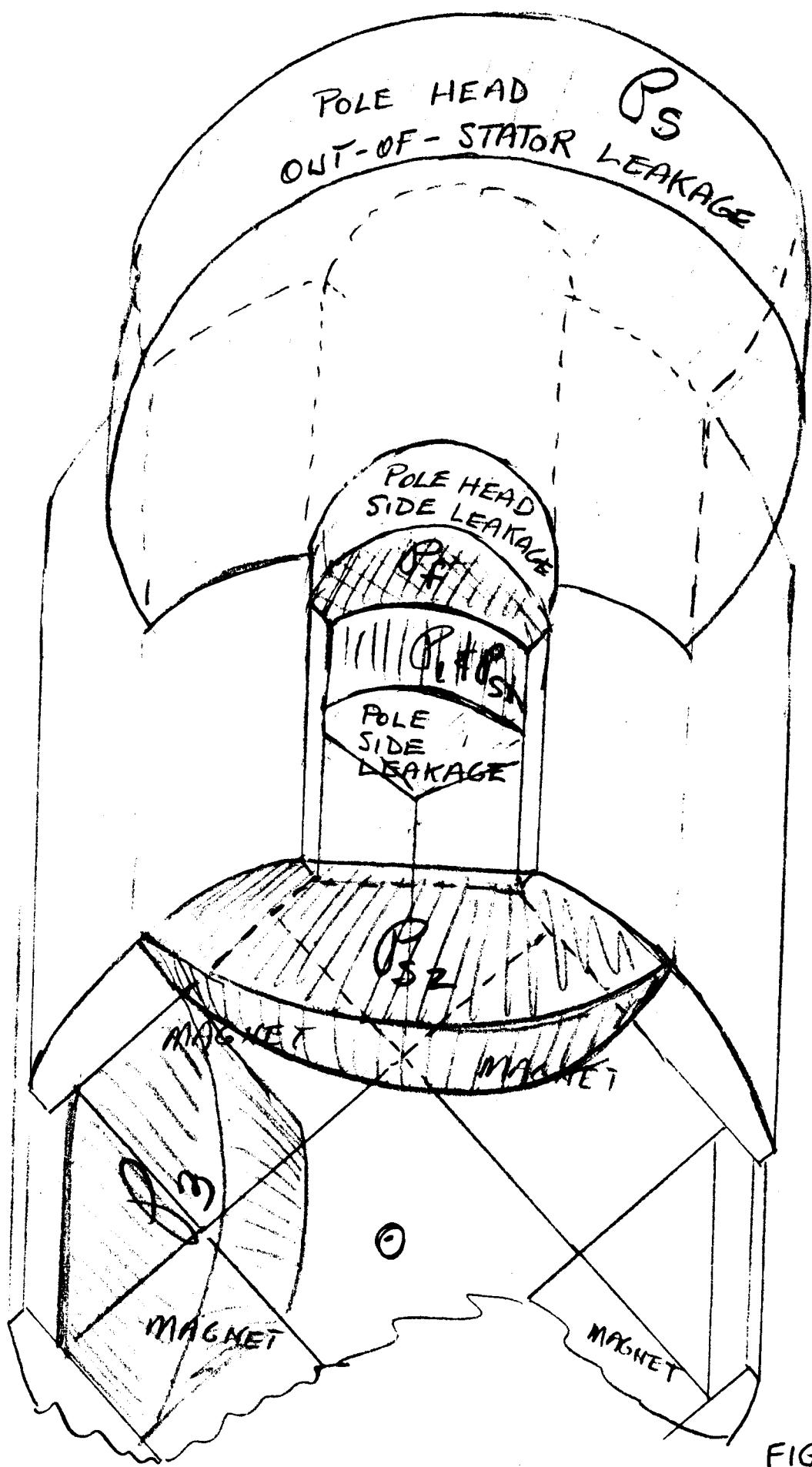


FIGURE XVIII

These rotor flux leakage permeances are separated into discrete leakage paths and are illustrated separately in the following sketches:

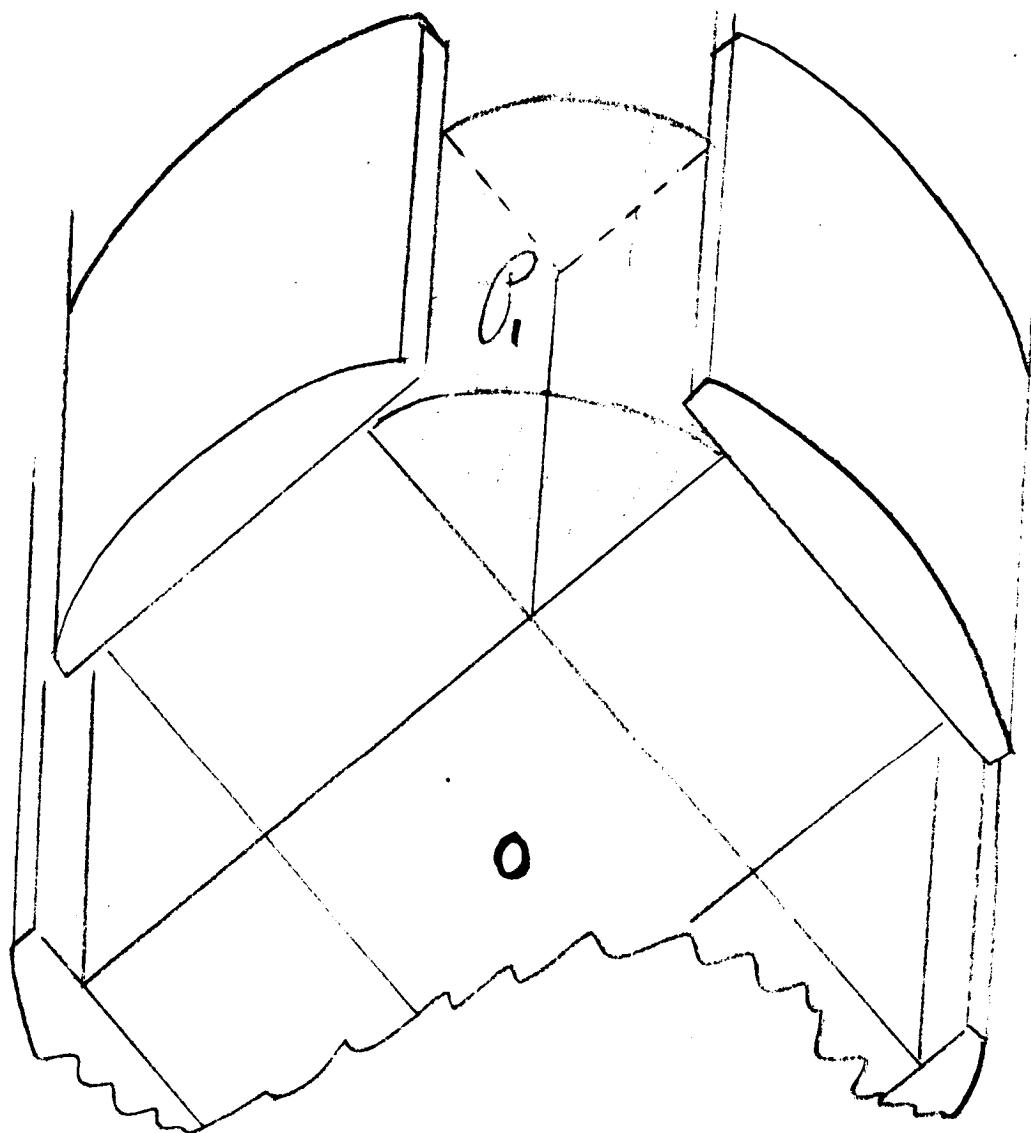


FIGURE XIX

P_1 = The pole-to-pole side leakage permeance. This leakage exists when the rotor is in the stator as well as when it is out and is just unuseable leakage flux.

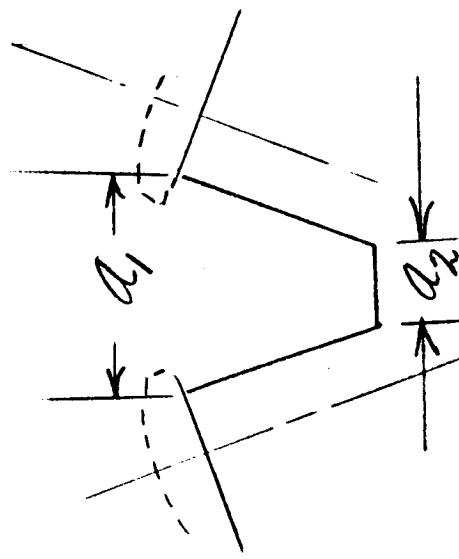
The formula here is taken from Strauss:

$$P_1 = 3.19 \frac{P}{\pi} \ell_p$$

for poles that touch at the base, and

$$P_1 = \ell_p \mu_0 \frac{P}{\pi} \left[1 - \frac{\alpha_2}{\alpha_1 - \alpha_2} \ln \left(1 + \frac{\alpha_1 - \alpha_2}{\alpha_2} \right) \right]$$

for poles not touching at the base.



$$P = \ell_p 3.19 \frac{P}{\eta} \left[1 - \frac{a_2}{a_1 - a_2} \log_e \left(1 + \frac{a_1 - a_2}{a_2} \right) \right]$$

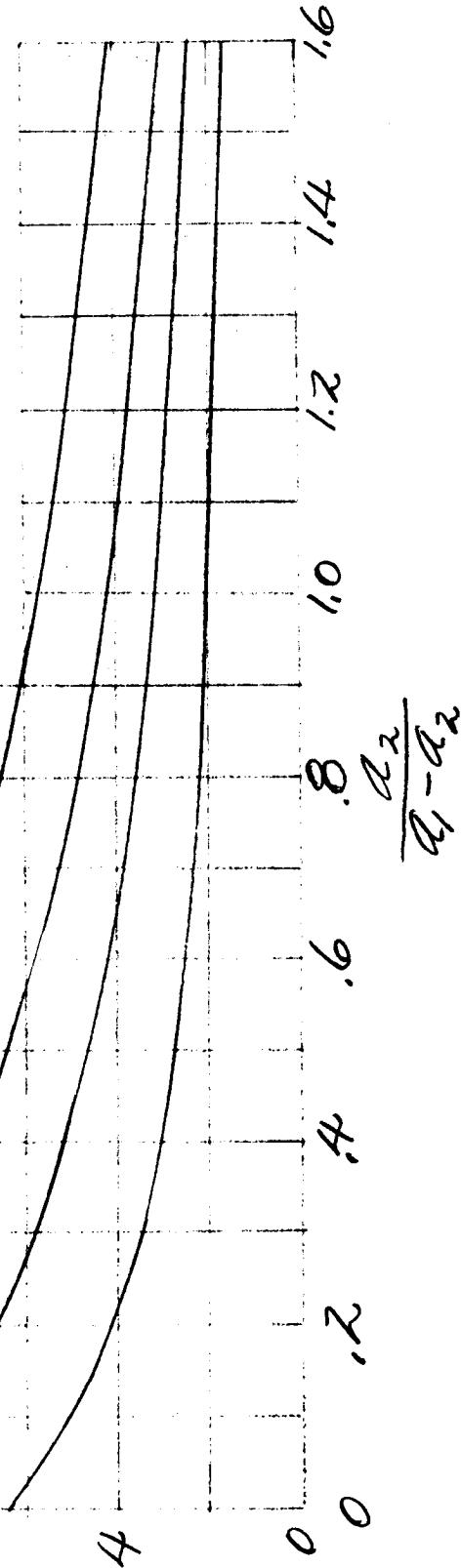
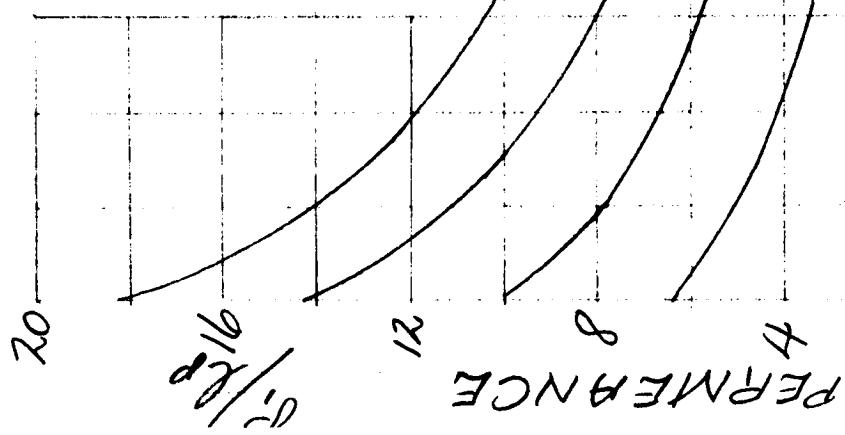
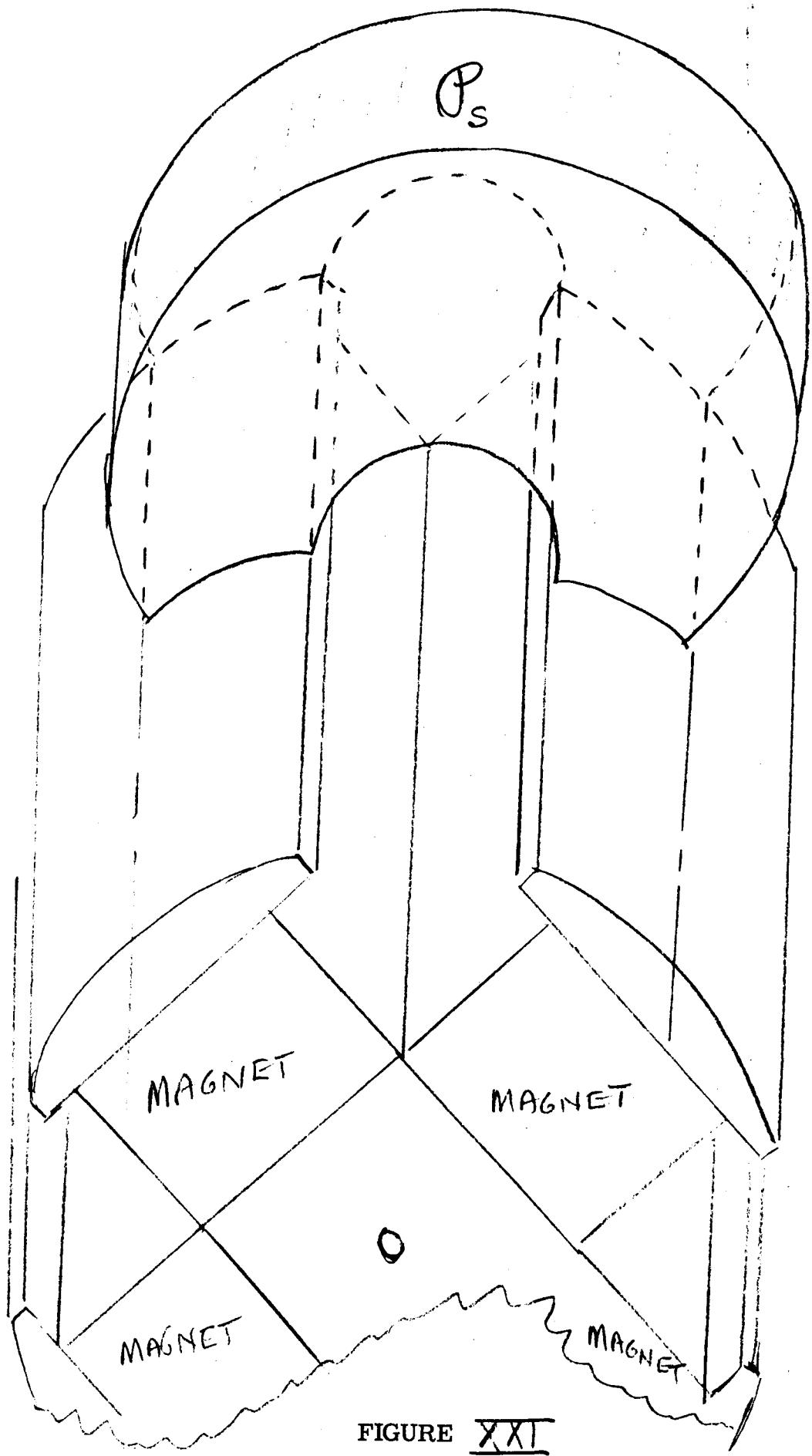


FIGURE XX



FIGURE XXI

P_s = the permeance of the flux leakage path from the centerline of one pole-head surface to the centerline of the adjacent pole-head surface.

This leakage is part of the out-stator leakage but does not exist when the rotor is inserted in the stator.

$$P_s = 2.03 l_p \ln \frac{T_r}{T_r - b_h}$$

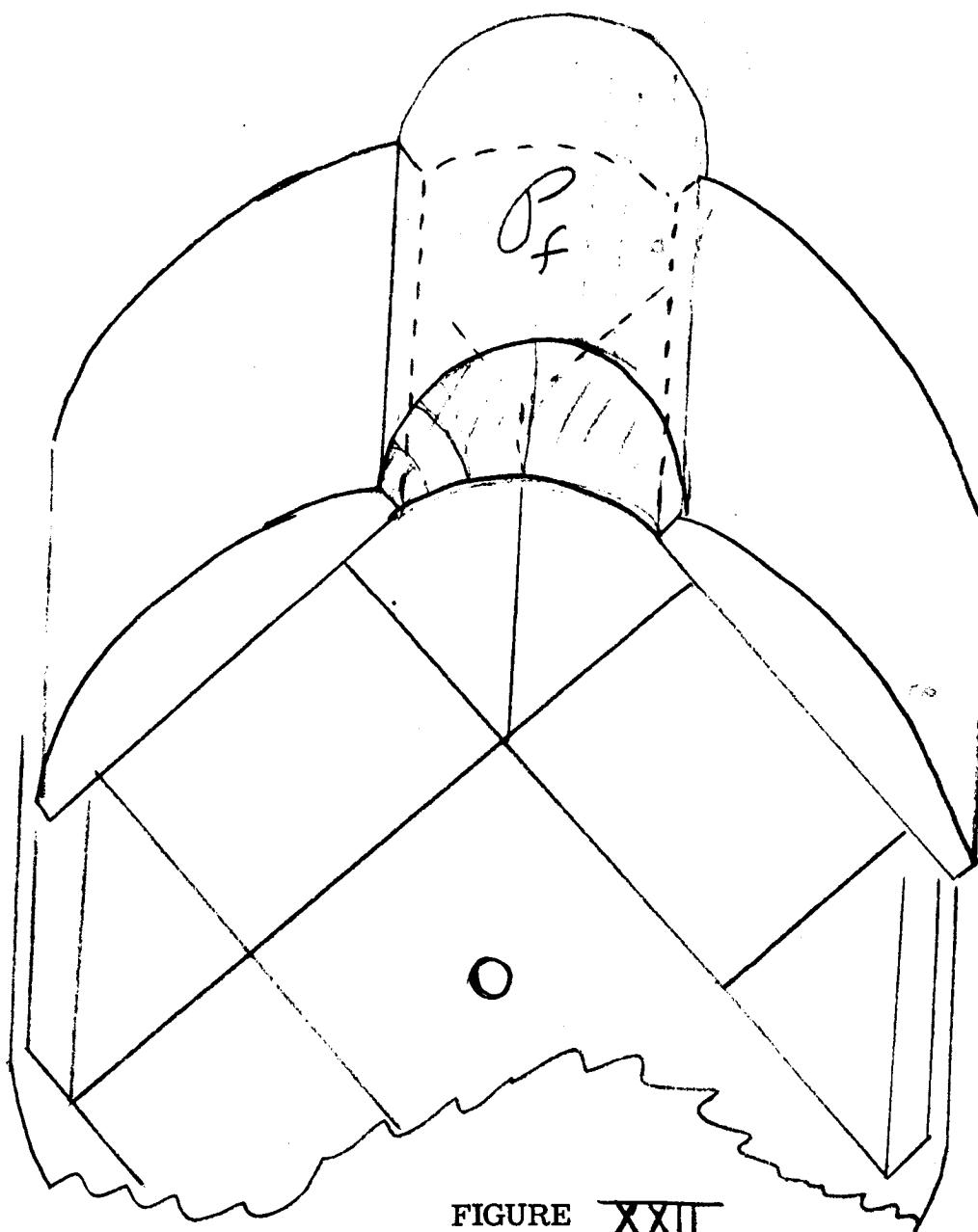


FIGURE XXI

P_f = the permeance of the flux leakage path between the adjacent ends of the pole heads.

This leakage flux is part of the out-stator leakage but no longer exists when the rotor is placed in the stator.

$$P_f = \mu_0 l_p \frac{0.322(\tau_r - b_h)}{1.220(\tau_r - b_h)} = 1.66$$

$$P_f = 1.66$$

$$\rho_x = \rho_s + \rho_f = l_p (1.66) (1 + 1.23 \log_e \frac{\ell}{\tau_r})$$

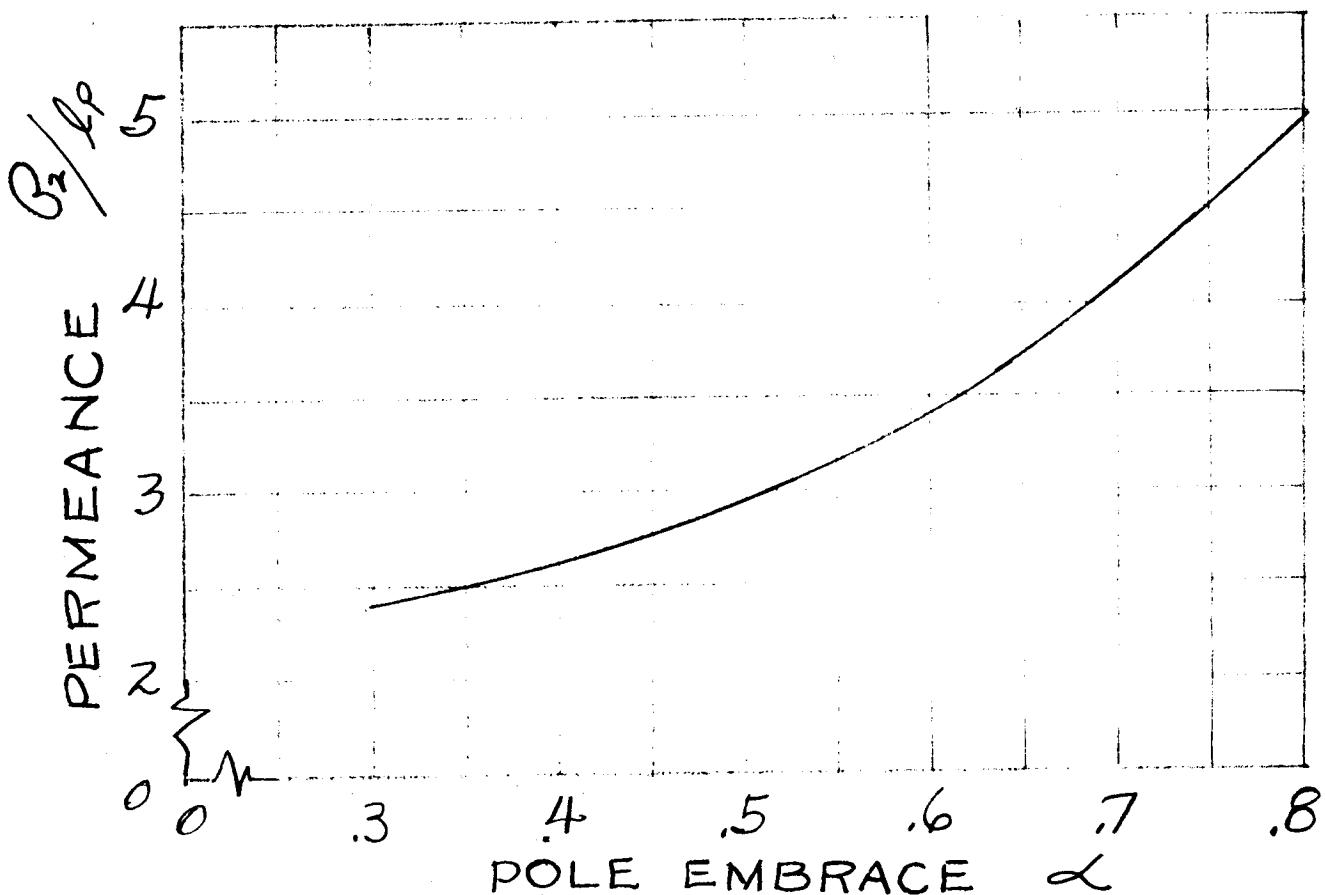


FIGURE XXIII

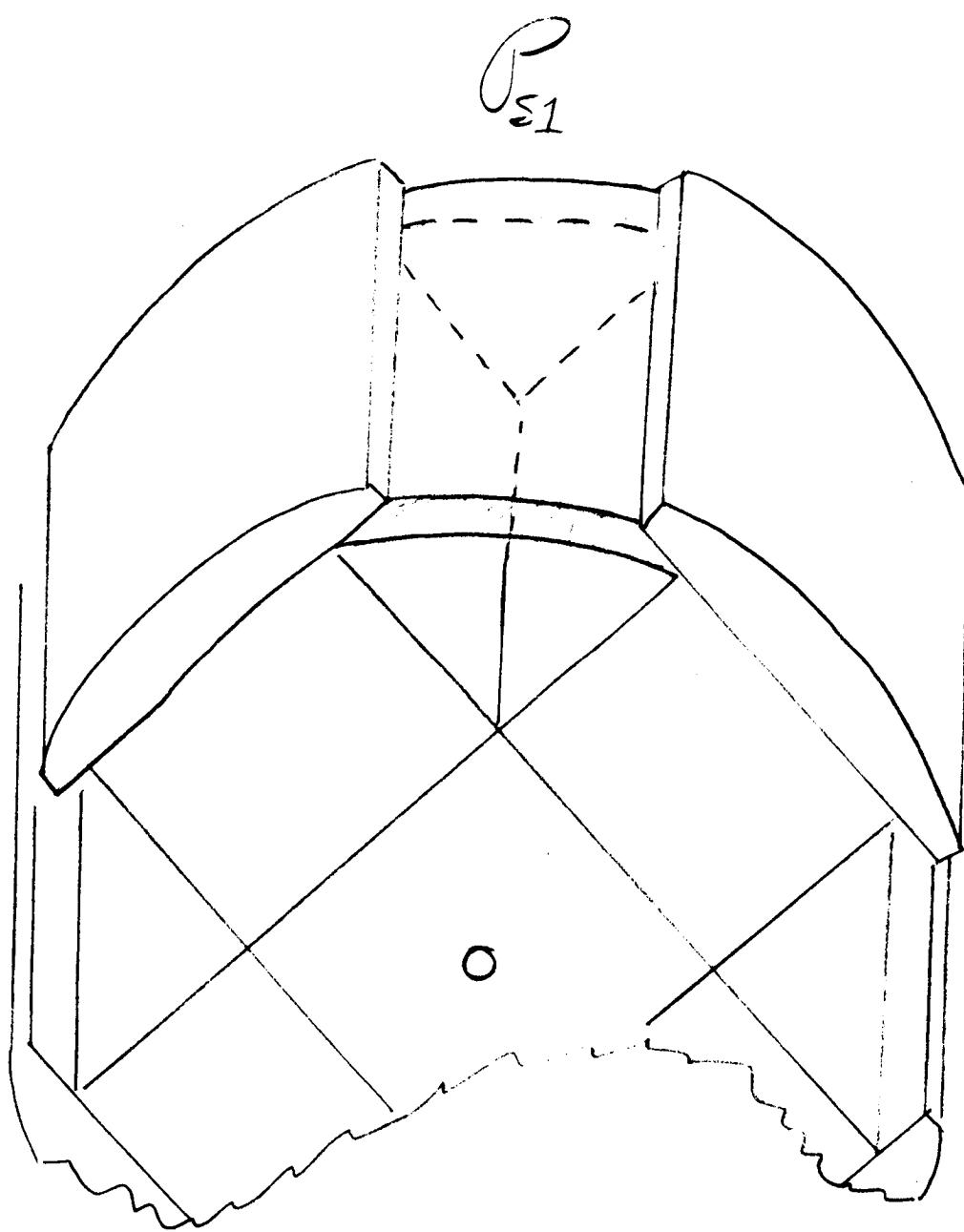


FIGURE XXIV

P_{s1} = the permeance of the flux leakage path from the underside of one pole shoe to the underside of the adjacent pole shoe.

This leakage is present when the rotor is in the stator and cannot be utilized.

$$P_{s1} = \frac{3.19 \frac{h_h l_p}{\pi d_r - b_p}}{\frac{P}{2}}$$

$$= \frac{6.38 \frac{h_h l_p}{T_r - b_p}}{}$$

The formula is an approximation, and is suitable for an estimate of the leakage between the pole heads of the usual four, six or eight pole design. For high leakage pole tips use as h_{h1} the height of the adjacent pole leakage surfaces. See the sketch for two examples.

SKETCH SHOWING HOW FLUX LEAKAGE CONDITIONS CHANGE WHEN EXTENDED POLE HEADS ARE USED. THE ADDED LEAKAGE KEEPS THE MAGNET DENSITY HIGH ON THE MAGNET CHARACTERISTIC MAJOR HYSTERESIS LOOP BUT THE ADDED LEAKAGE FLUX IS NEVER AVAILABLE FOR USE

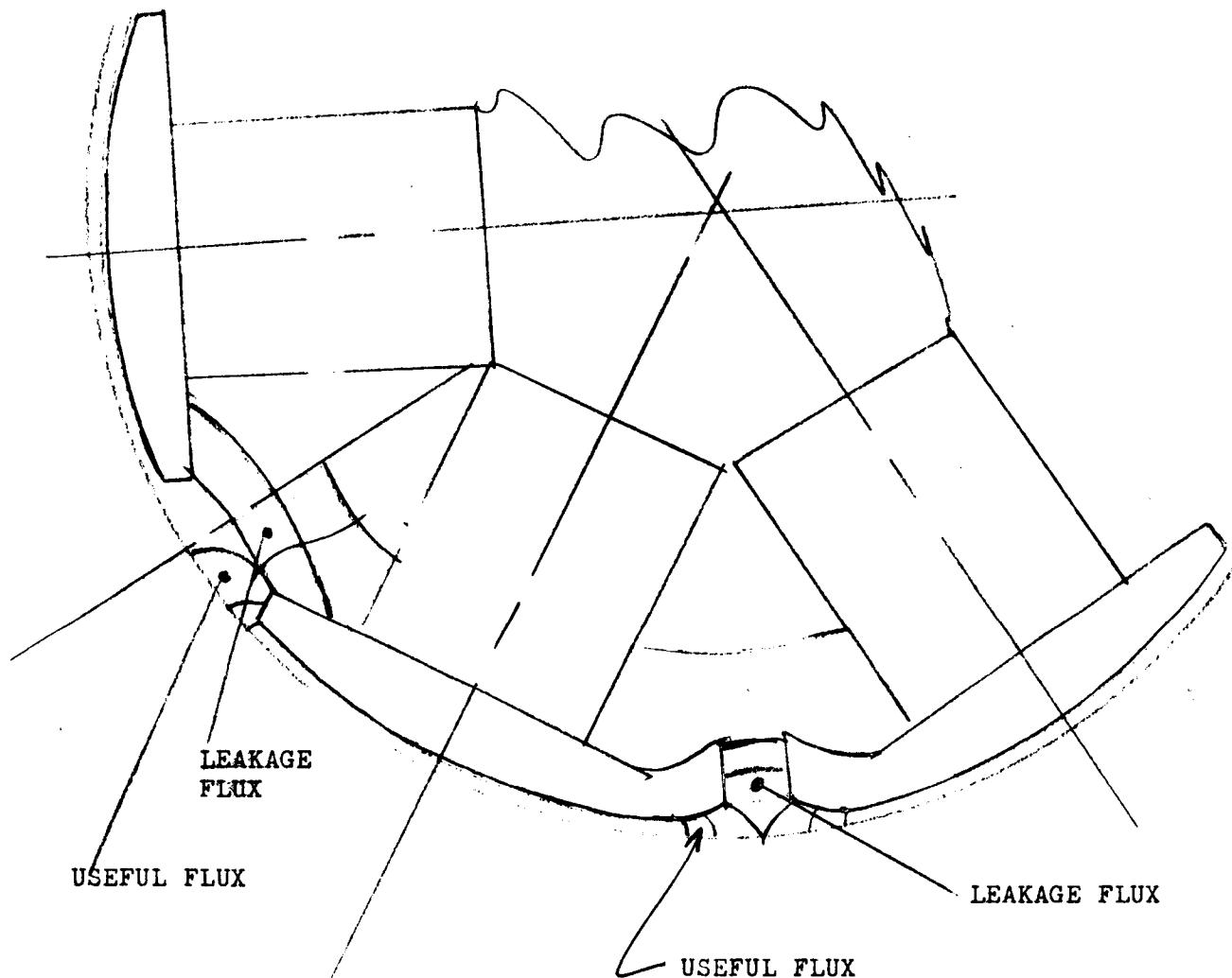
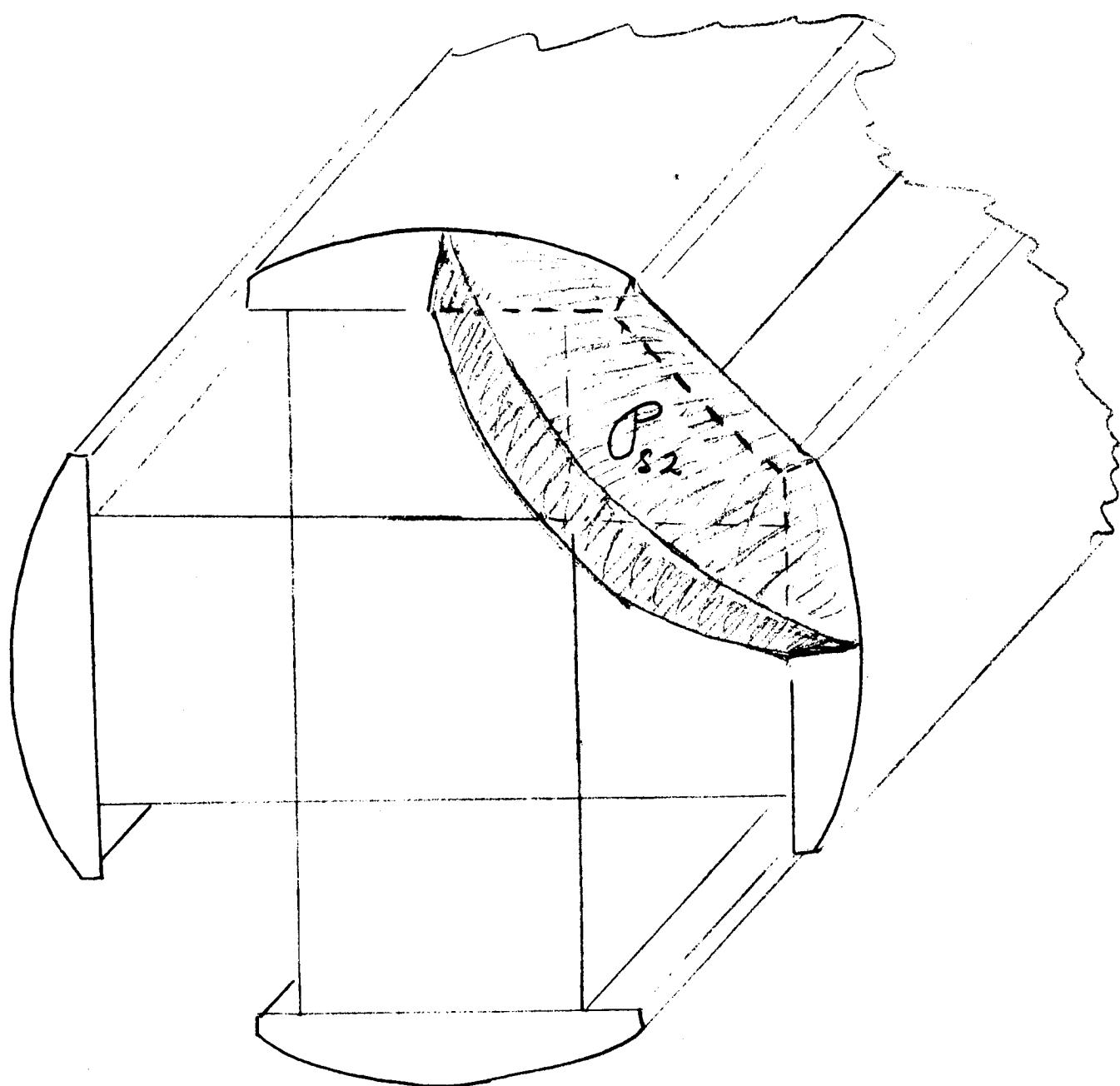


FIGURE XXV

FIGURE XXVI

P_{s2} = permeance of the flux leakage path from the centerline of the end surface of one pole head to the centerline of the end surface of the adjacent pole head.

This leakage flux is continuous and cannot be utilized in generating power.

$$P_{s2} = \frac{2 h_n P_2}{\ell_p} \quad \text{where}$$

$$P_2 = P_s + P_f$$

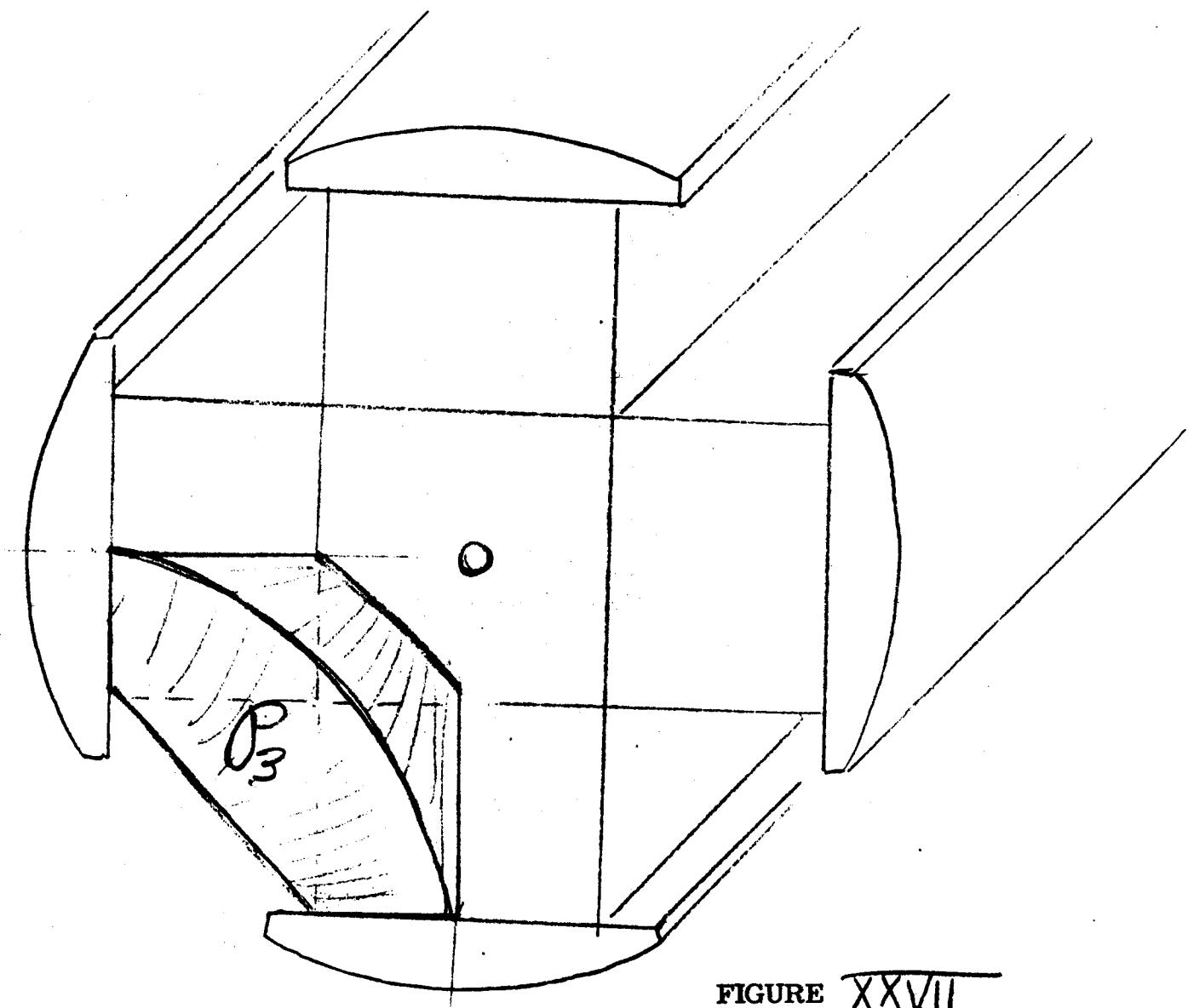


FIGURE XXVII

P_3 = the permeance of the flux leakage path from the centerline of the end surface of the pole to the centerline of the adjacent pole end surface.

This leakage flux is always present and cannot be utilized.

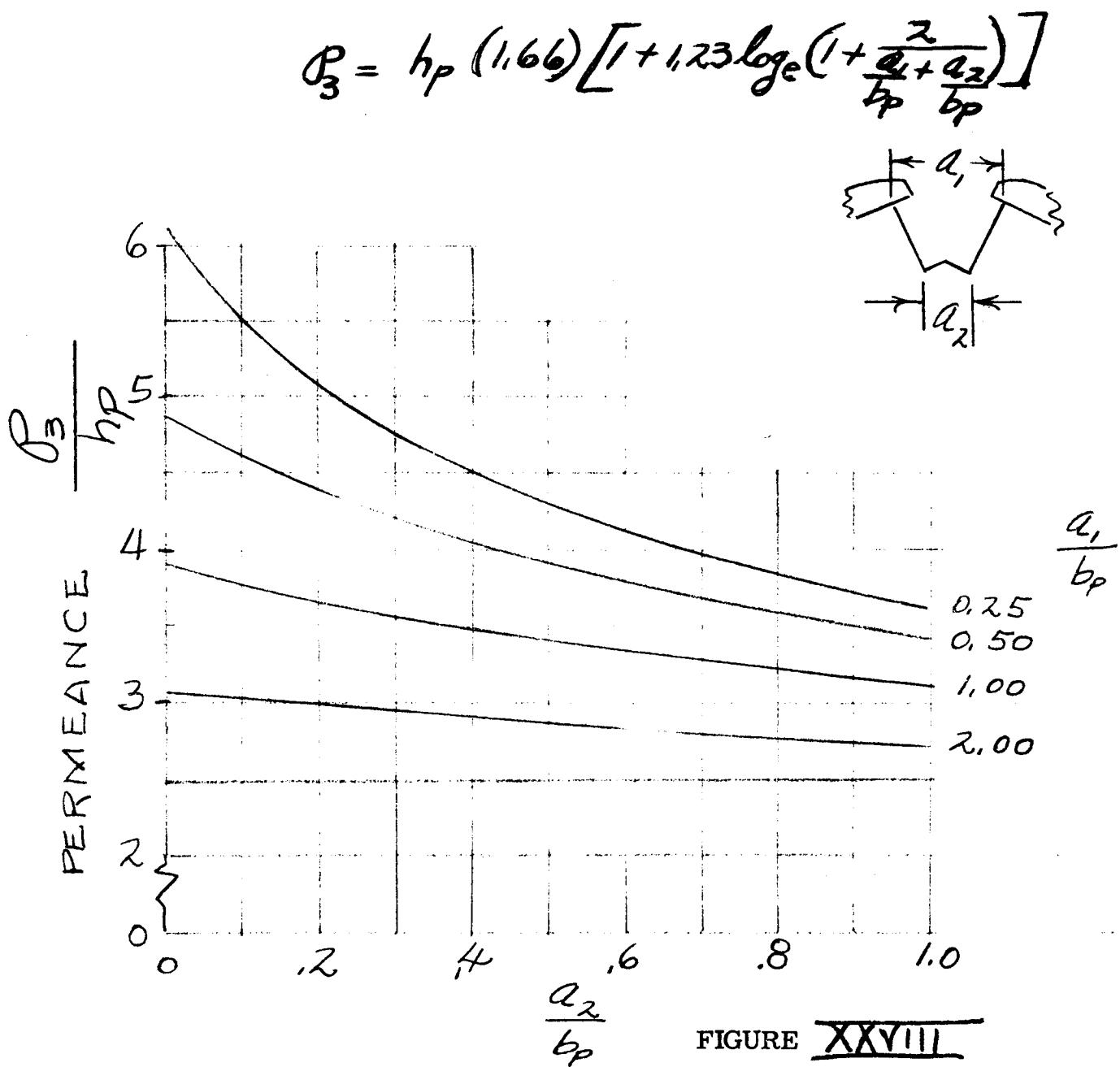


FIGURE XXVIII

When the rotor is inserted in the stator, the pole-to-pole flux that passed through the permeance paths, $P_s + P_f$ is no longer present as leakage flux. That flux now enters the stator and becomes useful flux.

All of the flux passing through the other pole-to-pole permeance paths is leakage flux that cannot be utilized.

$$P_i = \text{in-stator leakage permeance}$$

$$P_i = P_o - P_2$$

For convenience, the leakage permeance consisting of the sum of all the permeance paths, through which flux leaks pole-to-pole when the rotor is out of the stator is called P_o = out-stator permeance.

The sum of the pole-to-pole leakage permeance existing when the rotor is installed in the stator is called the in-stator permeance (P_i).

The permeances of the various flux paths have been calculated at this point in the design procedure. They could be used just as they are used in an electromagnetic generator in which case the magnet characteristics would be plotted in terms of total ampere-turns and total magnet flux. This procedure would require a special flux plot for each generator design.

An easier way to determine the magnet performance is to use the characteristic hysteresis loop as it is given by the manufacturer.

This loop is plotted in terms of ampere-turns per inch of magnet and flux-density per square inch of magnet.

The calculated permeances are already in terms of leakage flux per ampere turn and if the permeances are multiplied by the magnet length they can be then used in terms of ampere-turns per inch of magnet.

The leakage flux resulting from the calculation would be divided by magnet area to get the flux per square inch of magnet.

The calculation would look like this:

$$P \times \ell_m \times (\text{AT/in}) = \phi_{\ell}$$

$$\frac{P \times \ell_m \times (\text{AT/in})}{\text{Area of Magnet}} = \frac{\phi_{\ell}}{\text{in}^2}$$

$$\frac{P}{\frac{\text{Area Magnet}}{\ell_m}} = \frac{\phi_{\ell}/\text{in}^2}{\text{AT/in}}$$

$$\frac{P}{\frac{\ell_p b_p}{h_p}} = \frac{P}{P_m} = \frac{\phi_{\ell}/\text{in}^2}{\text{AT/in}}$$

$$\text{Where } P_m = \frac{\ell_p b_p}{h_p}$$

The ideal permanent magnet generator might have high flux leakage in the rotor when the rotor was out-of-stator and low flux leakage when the rotor was inserted in the stator, except that the machine would, in nearly all cases be capable of demagnetizing itself when subjected to a transient or short circuit.

The two following sketches illustrate how a choice is made between magnet materials just on the basis of the out-of-stator leakage characteristic.

The in-stator leakage must be considered in determining whether or not the generator can withstand short circuits and transients without loss of properties.

COMPARISON OF MAGNET PERFORMANCES WHEN AIR-STABILIZED AT A HIGH OUT-OF-STATOR PERMEANCE

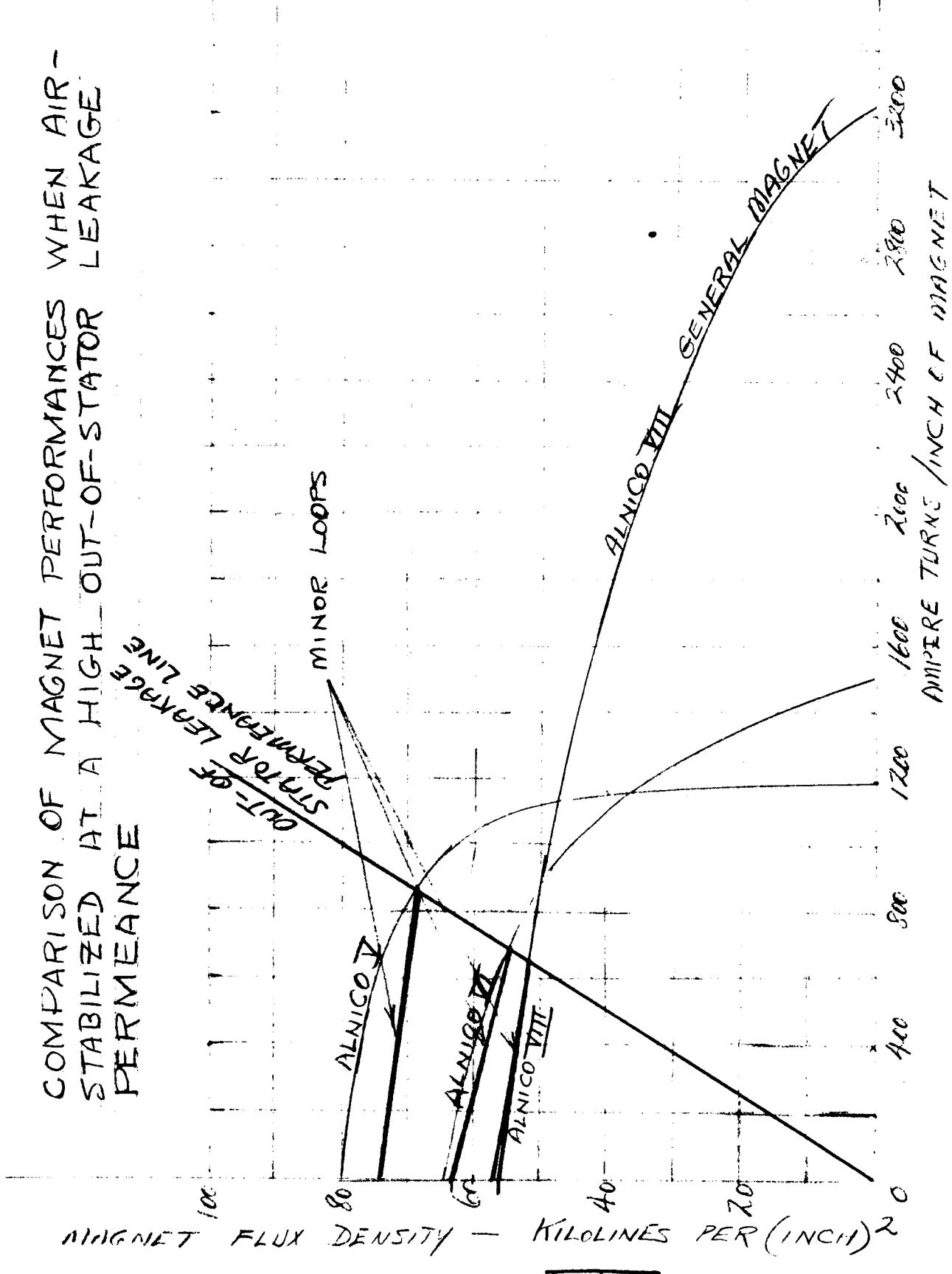


FIGURE XXIX

COMPARISON OF MAGNET PERFORMANCE AT A LOW OUT-OF-STATOR LEAKAGE PERMEANCE

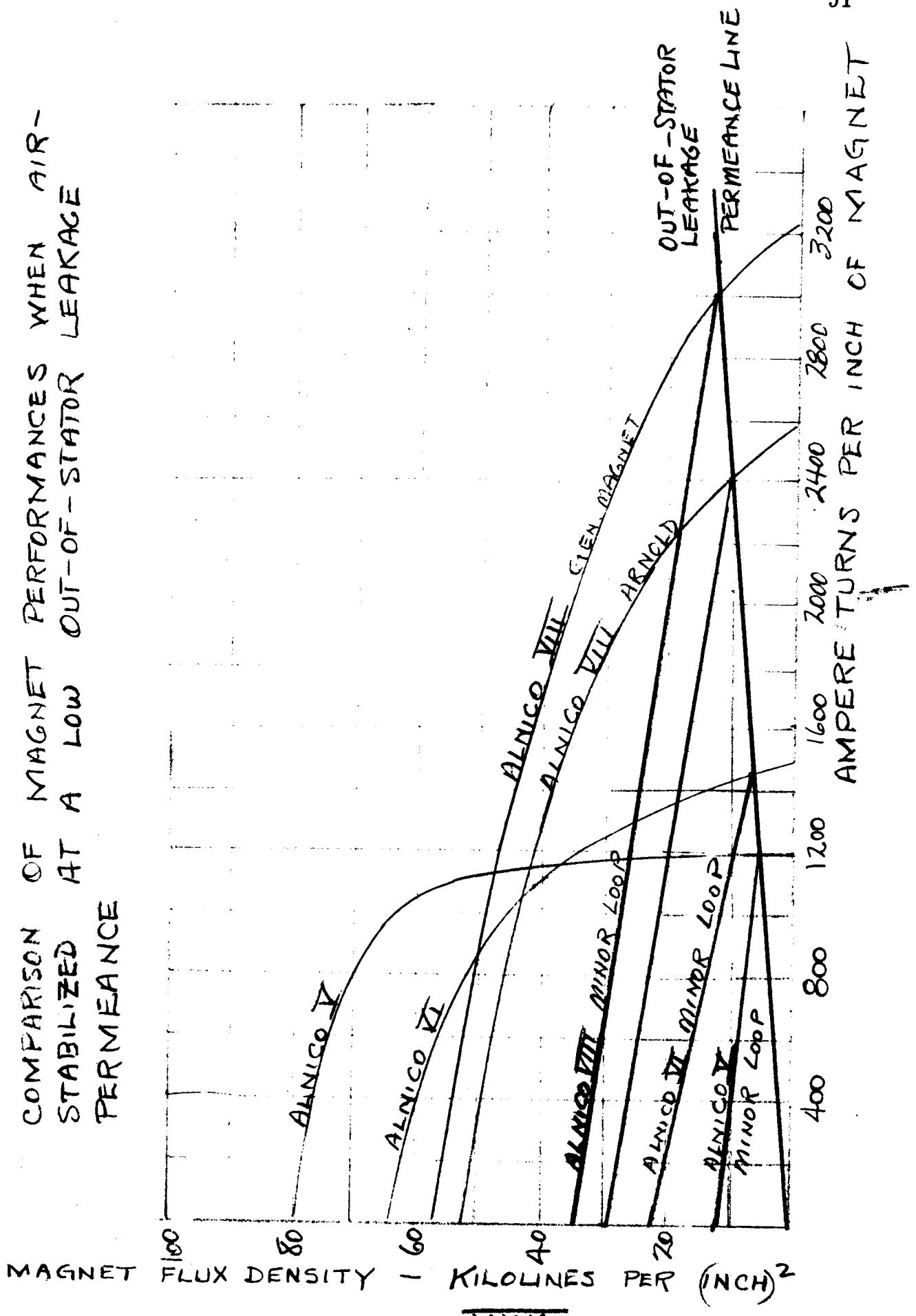


FIGURE XXX

DESIGNING A PM GENERATOR

To start a permanent magnet generator design:

1. Assume an ampere loading of 250. That is, 250 ampere wires per inch around the bore periphery. The symbol is A.
2. Assume an air gap density of 20 Kilolines per square inch. The symbol is Bg.
3. The rating and speed are known so

$$KVA = \frac{d^2 \ell (RPM) A Bg}{90 \times 10^7}$$

d = rotor diameter

ℓ = stator stack length

or

$$d^2 \ell = \frac{90 \times 10^7 (KVA)}{RPM A Bg}$$

$$= \frac{90 \times 10^7 (KVA)}{RPM(250)20}$$

$$d^2 \ell = \frac{180 \times 10^5 (KVA)}{RPM}$$

4. Assume $\ell = \frac{1}{2} d$ Then $d^2 \ell = \frac{d^3}{2}$

And

$$d = \sqrt[3]{\frac{3.60 \times 10^5 KVA}{RPM}}$$

NOTE: Any value of ℓ can be assumed for a trial design but

$\ell = \frac{1}{2} d$ is a good place to start.

5. The frequency is known and, therefore, the poles are

$$P = \frac{120 f}{N} \quad \text{where}$$

P = No. of poles

f = frequency in CPS

N = RPM

6. A three-phase machine should have at least one (1) slot per phase per pole.

$$\text{Slots} = q P m$$

Where q = slots per phase per pole

P = Poles

m = number of phases

The slots per phase per pole, q can be an integer or can be an improper fraction if when reduced to its lowest terms the denominator can be divided into the number of poles an integral number of times but not three (3) for a three-phase machine.

Usually, if the q is an integer or has 2 in the denominator of the improper fraction the design can be made satisfactorily. As an example, if the machine has 6 poles and three phases, the total slots Q can be written $Q = P m q = 6 \times 3 \times 2-1/2$

= 45 slots

7. Machines operating at 400 cps cannot usually have conductors much thicker than .100 inches in depth because of eddy currents at full load. This is an oversimplified general statement but examination of the eddy factor formula in the design manual will show the factors involved.

Since the conductor is usually small and the rotor speeds high in 400 cps and higher frequency generators, it is desirable to use as many slots as can be easily punched and wound. The more slots there are, the less the load factor of pole face loss will be and the less the slot leakage reactance will be.

A good slot pitch to consider in a smaller 400 cps generator is about .30 inch and the minimum slot pitch might be .20 inch or

$$\begin{array}{c} \text{.20} < \tau_s < .35 \\ \text{Slots} = Q = \frac{\pi d}{.3} \end{array}$$

If this comes out satisfactorily, proceed. If not, use a smaller slot pitch.

Example: A 6 pole generator with a 3.0" stator bore

$$Q = \frac{\pi (3.0)}{.3} = 10 \frac{\pi}{.3} = 31$$

$6 \times 3 \times 2 = 36$, so either 36 or 45 slots would probably be used. If the winding could be more simply designed with 27 slots, that number might be used. The possible combinations are:

$6 \times 3 \times 1 = 18$	$\tau_s = .523$
$6 \times 3 \times 1-1/6 = 20$	$\tau_s = .47$
$6 \times 3 \times 1-1/2 = 27$	$\tau_s = .349$
$6 \times 3 \times 1-5/6 = 35$	$\tau_s = .269$
$6 \times 3 \times 2 = 36$	$\tau_s = .262$
$6 \times 3 \times 2-1/6 = 37$	$\tau_s = .254$
$6 \times 3 \times 2-1/2 = 45$	$\tau_s = .209$

8. Now we have the bore area and the flux density so the theoretical total flux is $\phi_T = Bg \times A_{\text{gap}} = Bg \pi d$

Then E_{LL} is known and the only unknown is the number of conductors needed

$$N_e = \text{effective conductors} = NK_p$$

$$N = \text{total conductors}$$

$$K_p = \text{pitch factor}$$

$$N_e = \frac{60 \times 10^5 E_{LL}}{\text{RPM} (C_w) \phi_T}$$

$$N = \frac{N_e}{K_p}$$

$K_p = .866$ for $2/3$ pitch and about $.960$ for longer pitches

$$N_s = \frac{N}{Q} = \text{conductors per slot}$$

N_s must be an even number if a series circuit is used because there are two coil sides per slot in a normal winding. To make the winding suitable for the machine, parallel windings can be used or the number of slots can be varied as explained previously. If these efforts do not produce a satisfactory winding combination, the diameter of the generator can be changed and the stack length changed also to give about the same d^2l .

9. The slot area is a variable that is dependent upon the tooth flux. Enough tooth must be provided to assure mechanical integrity and to keep the flux density to about 100 K₁ at 400 cps no load - less at higher frequencies.

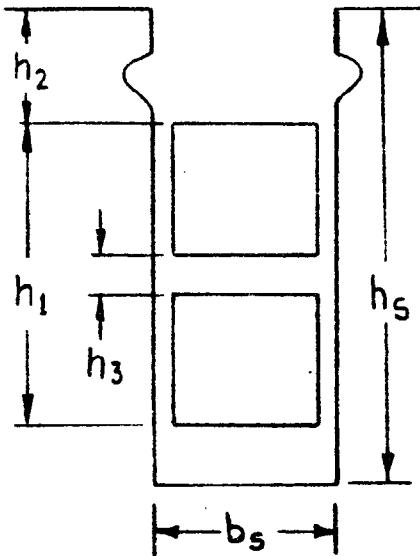
Make a preliminary calculation of tooth area as instructed in the design manual and then using the number of conductors calculated previously in step 8, size the conductors so that the current density is acceptable. For air-cooled designs, the current density allowable may be 10,000 amperes per square inch or slightly more. For high temperature machines or poorly cooled machines, the current density may be as low as 2000-3000 amperes per square inch.

10. The slot size and shape is determined by the space available between teeth, and conductor and insulation requirements. Semi-closed slots are often wound through the opening by using small wire,

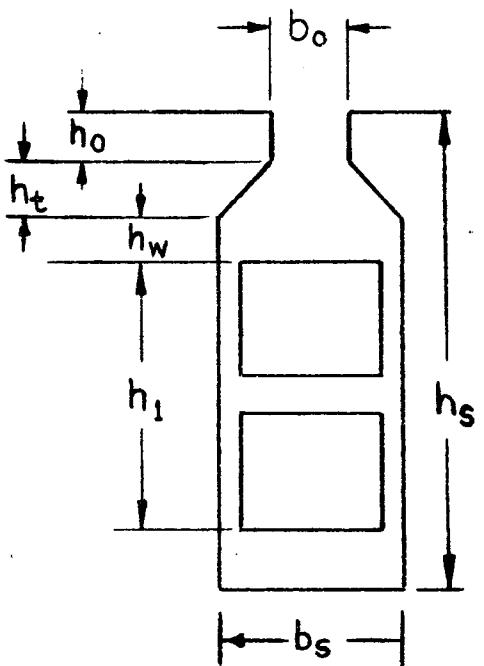
Several strands in-hand or in parallel. If only two wires per slot are necessary push-through windings can be easily managed. The large commercial generators are almost always made with open slots for winding ease. Allow .050" over the bare conductor width for slot cell and conductor insulation and about .100" over the vertical conductor total dimension to allow for insulation, a center stick and a top stick.

11. Most of the information is now provided for the computer program and a trial design calculation can be made.
12. Repeat the above procedure for ampere loadings of 250, 300, 400 and then fix the density in the gap at 25 K/in^2 and repeat the calculations. Do the series of trials again for $B_g = 30 \text{ K/in}^2$. From an examination of the results of these trials, the proper parameters can be selected.

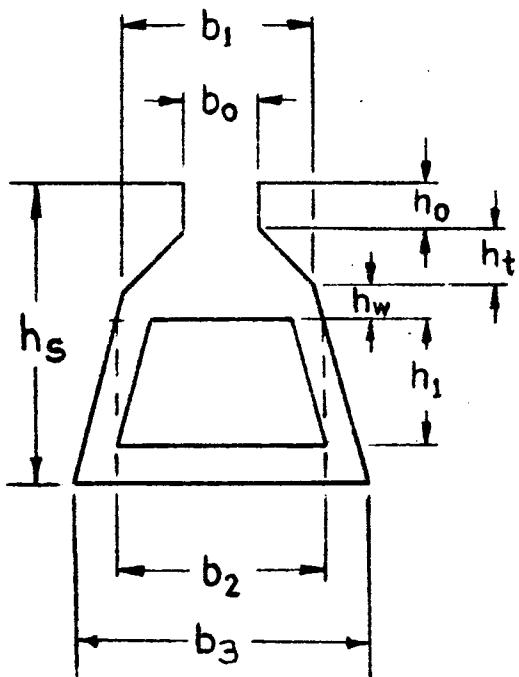
(a) Open Slots



(b) Constant Slot Width



(c) Constant Tooth Width



(d) Round Slots

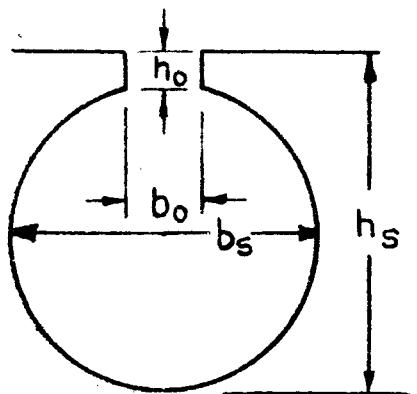


FIG 1

P. M. GENERATOR DESIGN MANUAL

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TABLE - 1

g_i	γ_{avg}	K_0 For Harmonics At Different Pitches
1	3/3	7/11
2	6/6	7/9
3	9/9	10/12
4	12/12	13/15
5	15/15	16/16
6	18/18	17/18
7	21/21	19/21
8	24/24	21/24
9	27/27	23/27
10	30/30	25/30
11	33/33	27/33
12	36/36	29/36
13	39/39	31/39
14	42/42	33/42
15	45/45	35/45
16	48/48	37/48
17	51/51	39/51
18	54/54	41/54
19	57/57	43/57
20	60/60	45/60
21	63/63	47/63
22	66/66	49/66
23	69/69	51/69
24	72/72	53/72
25	75/75	55/75
26	78/78	57/78
27	81/81	59/81
28	84/84	61/84
29	87/87	63/87
30	90/90	65/90
31	93/93	67/93
32	96/96	69/96
33	99/99	71/99
34	102/102	73/102
35	105/105	75/105
36	108/108	77/108
37	111/111	79/111
38	114/114	81/114
39	117/117	83/117
40	120/120	85/120
41	123/123	87/123
42	126/126	89/126
43	129/129	91/129
44	132/132	93/132
45	135/135	95/135
46	138/138	97/138
47	141/141	99/141
48	144/144	101/144
49	147/147	103/147
50	150/150	105/150
51	153/153	107/153
52	156/156	109/156
53	159/159	111/159
54	162/162	113/162
55	165/165	115/165
56	168/168	117/168
57	171/171	119/171
58	174/174	121/174
59	177/177	123/177
60	180/180	125/180
61	183/183	127/183
62	186/186	129/186
63	189/189	131/189
64	192/192	133/192
65	195/195	135/195

n	K_{dn} - HARMONIC DISTRIBUTION FACTORS										
$g =$	2	3	4	5	6	7	8	9	10	∞	
1	.966	.966	.958	.957	.957	.957	.956	.955	.955	.955	
3	.707	.667	.654	.646	.644	.642	.641	.640	.639	.636	
5	.259	.217	.205	.200	.197	.195	.194	.194	.193	.191	
7	-.259	-.177	-.158	-.149	-.145	-.143	-.141	-.140	-.140	-.136	
9	-.707	-.333	-.270	-.247	-.236	-.229	-.225	-.222	-.220	-.212	
11	-.966	-.177	-.126	-.110	-.102	-.097	-.095	-.093	-.092	-.087	
13	-.966	.217	.126	.102	.092	.086	.083	.081	.079	.073	
15	-.707	.667	.270	.200	.172	.158	.150	.145	.141	.127	
17	-.259	.960	.158	.102	.084	.075	.070	.066	.064	.056	
19	.259	.960	-.205	-.110	-.084	-.072	-.066	-.062	-.060	-.059	
21	.707	.667	-.654	-.247	-.172	-.143	-.127	-.118	-.112	-.091	
23	.966	.217	-.958	-.149	-.092	-.072	-.063	-.057	-.054	-.041	
25	.966	-.177	-.958	.200	.102	.075	.063	.056	.052	.038	
27	.707	-.333	-.654	.646	.236	.158	.127	.111	.101	.071	
29	.259	-.177	-.205	.957	.145	.086	.066	.056	.050	.033	
31	-.259	.217	.158	.957	-.197	-.097	-.070	-.057	-.050	-.031	

33	-.707	.667	.270	.646	-.644	-.229	-.150	-.118	-.101	-.058
35	-.966	.960	.126	.200	-.957	-.143	-.083	-.062	-.052	-.027
37	-.966	.960	-.126	-.199	-.957	.195	.095	.066	.054	.026
39	-.707	.667	-.270	-.247	-.644	.642	.225	.145	.112	.099
41	-.259	.217	-.158	-.110	-.197	.957	.141	.081	-.060	.023
43	.259	-.177	.205	.102	.145	.957	-.194	-.093	-.064	-.022
45	.707	-.333	.654	.200	.236	.642	-.641	-.222	-.141	-.042
47	.966	-.177	.958	.102	.102	.195	-.956	-.140	-.079	-.020
49	.966	.217	.958	-.110	-.092	-.143	-.956	.194	.092	.019
51	.707	.667	.654	-.247	-.172	-.229	-.641	.640	.220	.038
53	.259	.960	.205	-.149	-.084	-.097	-.194	.955	.140	.018
55	-.259	.960	-.158	.200	.084	.086	.141	.955	-.193	-.017
57	-.707	.667	-.270	.646	.172	.158	.225	.640	-.639	-.033
59	-.966	.217	-.126	.957	.092	.075	.095	.194	-.955	-.016
61	-.966	-.177	.126	.957	-.102	-.072	-.083	-.140	-.955	.016
63	-.707	-.333	.270	.646	-.236	-.143	-.150	-.222	-.639	.030
65	-.259	-.177	.158	.200	-.145	-.072	-.070	-.093	-.193	.015

P. M. GENERATOR DESIGN MANUAL
ROUND COPPER WIRE

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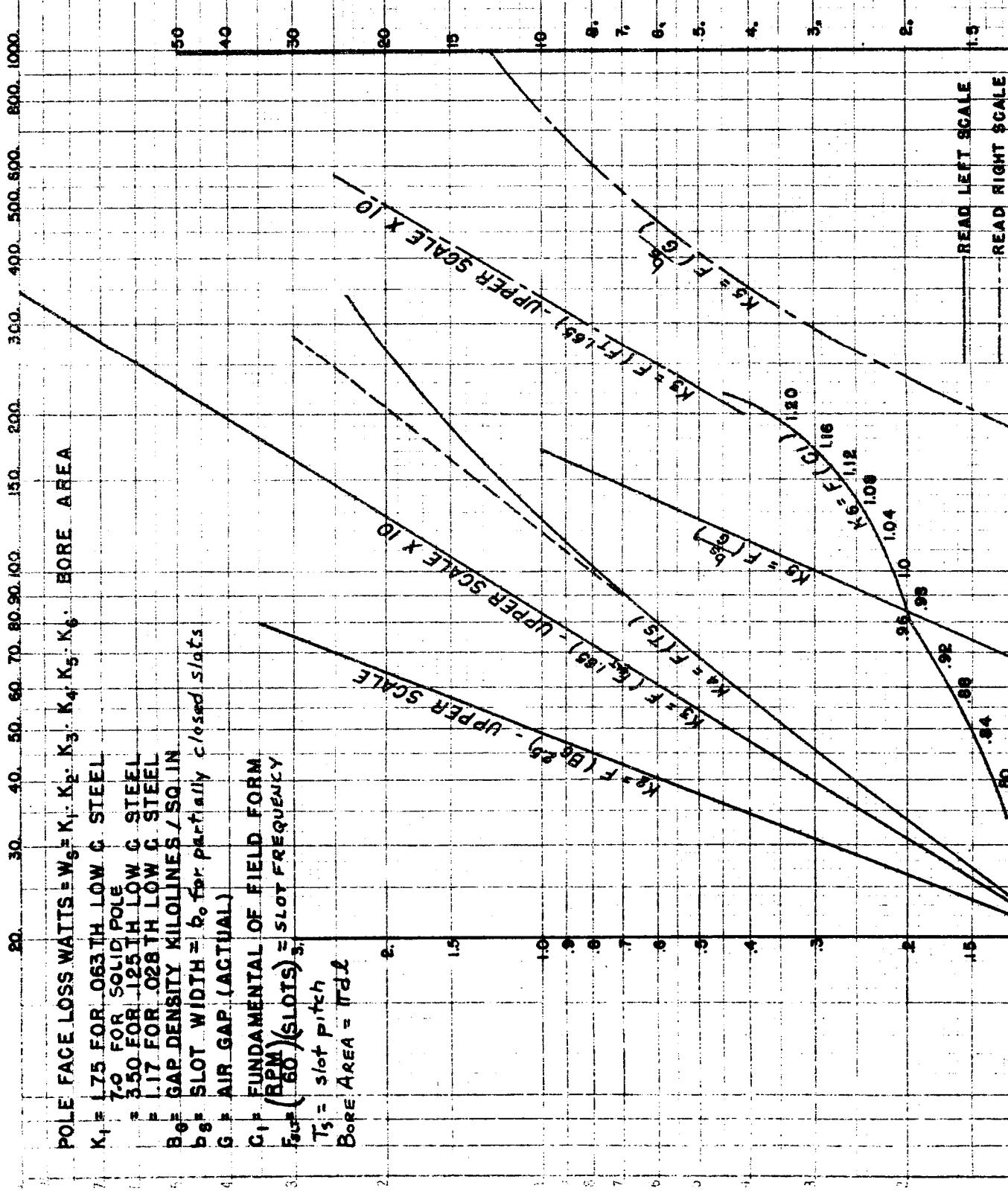
TABLE 3

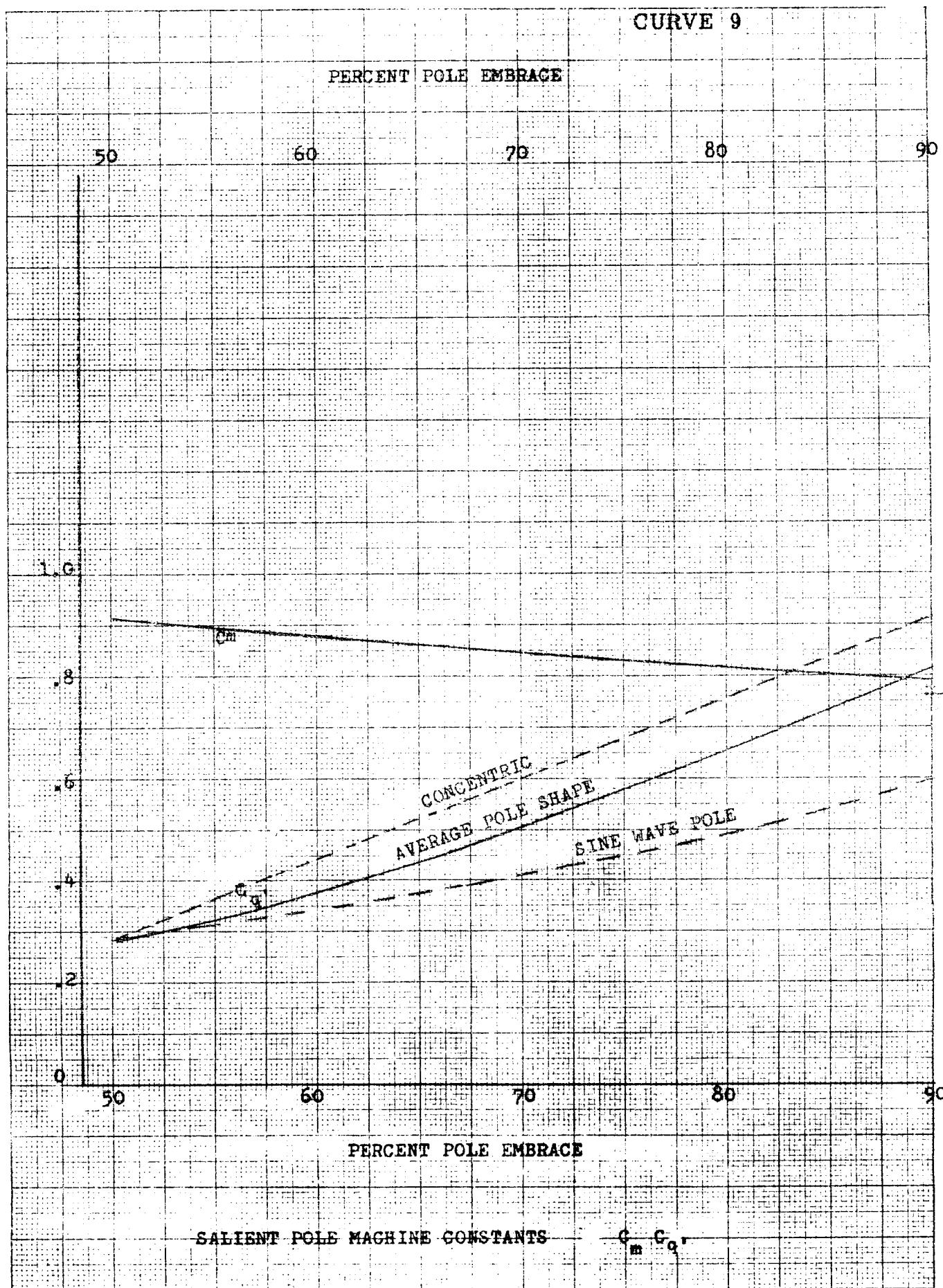
SIZE AWG	BARE DIAMETER	AREA sq"	$\Omega /1000'$ $@25^\circ C$	SINGLE FORMVAR	HEAVY FORMVAR	SINGLE GLASS FORMVAR	BARE WT. #/1000'	SINGLE GLASS SILICONE	DOUBLE GLAS SILICONE
36	.0050	.0000196	424	.0056	.0060		.0757		
35	.0056	.0000246	338	.0062	.0066		.0949		
34	.0063	.0000312	266	.0070	.0074		.1201		
33	.0071	.0000396	210	.0079	.0084		.1526		
32	.0080	.0000503	165	.0088	.0094	.0121	.1937		
31	.0089	.0000622	134	.0097	.0104	.0130	.2398		
30	.0100	.0000785	106	.0108	.0116	.0142	.3025	.0132	.0152
29	.0113	.000100	83.1	.0122	.0130	.0156	.3866	.0145	.0165
28	.0126	.000125	66.4	.0135	.0144	.0169	.4806	.0158	.0178
27	.0142	.000158	52.6	.0152	.0161	.0186	.6101	.0174	.0194
26	.0159	.000199	41.7	.0169	.0179	.0203	.7650	.0191	.0211
25	.0179	.000252	33.0	.0190	.0200	.0224	.970	.0211	.0231
24	.0201	.000317	26.2	.0213	.0223	.0263	1.223	.0251	.0276
23	.0226	.000401	20.7	.0238	.0249	.0289	1.546	.0276	.0301
22	.0254	.000507	16.4	.0266	.0277	.0317	1.937	.0303	.0328
21	.0285	.000638	13.0	.0299	.0310	.0349	2.459	.0335	.0360
20	.0320	.000804	10.3	.0334	.0346	.0384	3.099	.0370	.0395
19	.0360	.00102	8.14	.0374	.0386	.0424	3.900	.0409	.0434
18	.0403	.00126	6.59	.0418	.0431	.0468	4.914	.0453	.0478
17	.0453	.00159	5.22	.0469	.0482	.0519	6.213	.0503	.0528
16	.0508	.00204	4.07	.0524	.0538	.0575	7.812	.0558	.0583
15	.0571	.00255	3.26	.0588	.0602	.0639	9.87	.0621	.0646
14	.0641	.00322	2.58	.0659	.0673	.0710	12.44	.0691	.0716
13	.072	.00407	2.04	.0738	.0753	.0789	15.69	.0770	.0795
12	.0808	.00515	1.61	.0827	.0842	.0877	19.76	.0858	.0883
11	.0907	.00650	1.28	.0927	.0942	.0977	24.90	.0957	.0982
10	.102	.00817	1.02	.1039	.1055	.1089	31.43	.1069	.1094
9	.114	.0102	.814	.1165	.1181	.1225	39.62	.1204	.1254
8	.129	.0131	.634	.1306	.1323	.1366	49.98	.1345	.1395
7	.144	.0163	.510	.1465	.1482	.1525	63.03	.1503	.1553
6	.162	.0206	.403	.1643	.1661	.1703	79.44	.1680	.1730
5	.182	.0260	.319	.1842	.1861	.1902	100.2	.1879	.1929
4	.204	.0327	.254				126.3	.2103	.2153
3	.229	.0412	.202				159.3		
2	.258	.0523	.159				200.9		
0	.325	.0830	.100						
2/0	.365	.105	.0791						
4/0	.460	.166	.0500						

P. M. GENERATOR DESIGN MANUAL
CURVE 2

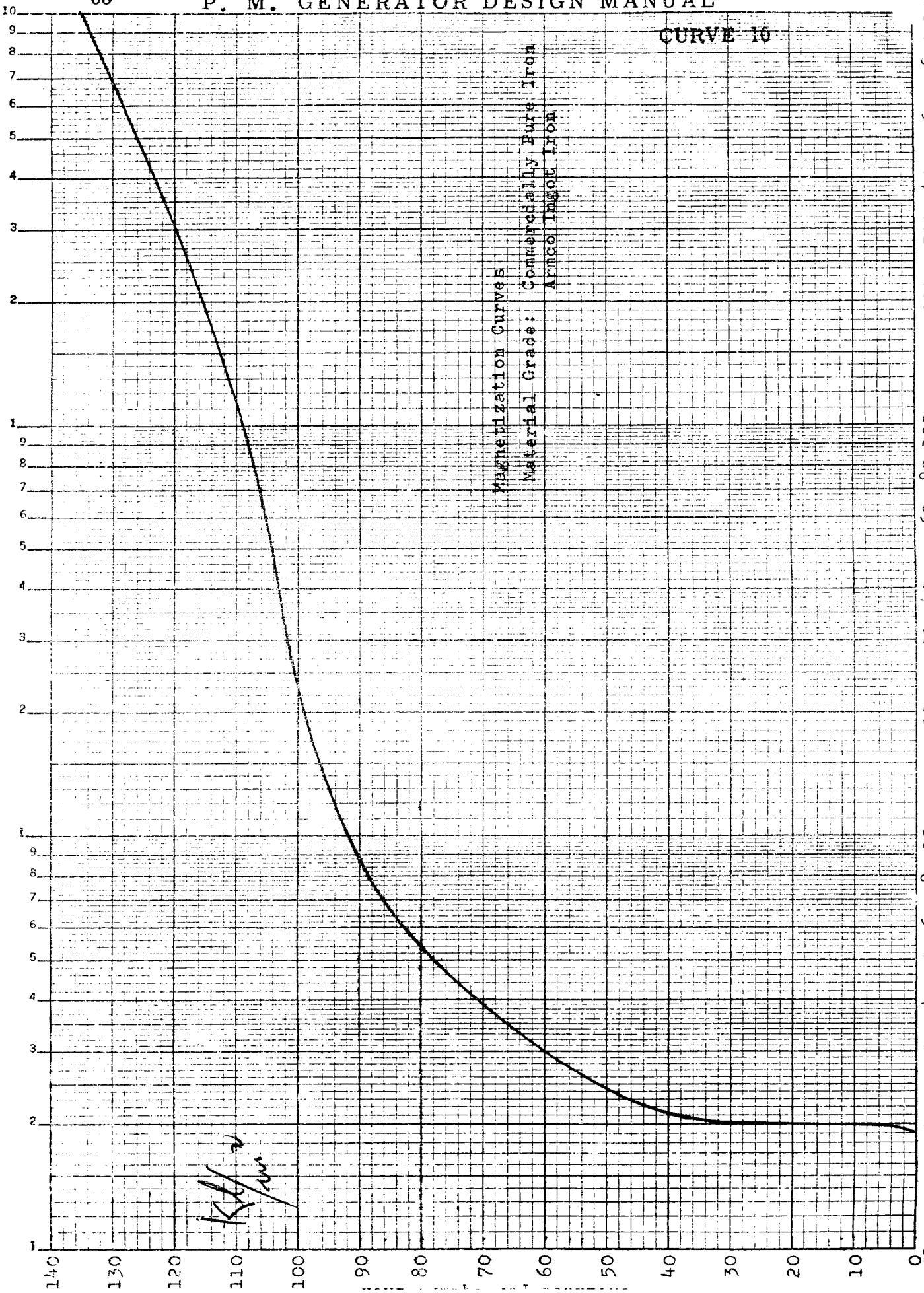
From Kennard and Spooner "Surface Iron Losses with Respect to Laminated Materials", Trans. AIEE, Vol. 43, 1924,
pp 262-281.

REFER TO ITEM (150) IN SALIENT POLE DESIGN MANUAL FOR
SAMPLE USE OF THIS CURVE





CURVE 10



NO-LOAD DAMPER LOSS

CURVE 7

$$D.L. = \frac{1.246 P n_b l_b P}{10^6 A_b} \left[I_s B_g K_p K_g \right]^{1/2} \left[\frac{K_{\phi_1}/K_{\omega_1}}{(2\lambda_s + \frac{\lambda_g}{K_{\phi_1}})} \right]^2 + \left[\frac{K_{\phi_2}/K_{\omega_2}}{(2\lambda_s + \frac{\lambda_g}{K_{\phi_2}})} \right]^2$$

LOSS IN KW

$$\lambda_s = \frac{hr}{br} + \lambda_t + \lambda_c$$

A_b = BAR AREA IN SQ. IN.

n_b = BARS/POLE

P = NO. POLES

l_b = LENGTH BAR IN.

$$\lambda_g = \frac{t_b}{k_g g} = \frac{t_b}{g'}$$

K_g = CARTER'S COEFFICIENT (TOTAL)

$K_p = f_n(b_s/g)$, CURVE (a) ($b_s + b_o$ for partially closed slots)

K_{ϕ_1} AND $K_{\phi_2} = f_n(f_s/f)$ CURVE (b)

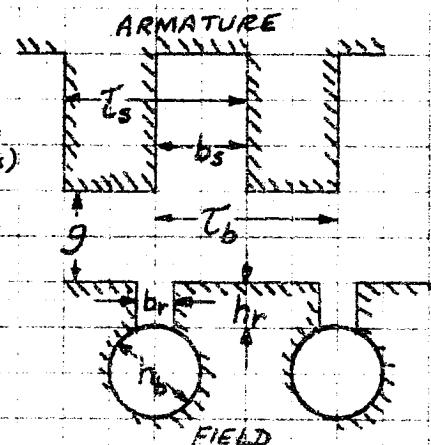
ρ = DAMPER BAR RESISTIVITY
(MICROHMS PER CU. IN.)

K_{ω_1} AND $K_{\omega_2} = f_n(b_s/I_s)$, CURVE (c₁) AND (c₂)

K_{ϕ_1} AND $K_{\phi_2} = f_n(t_b/I_s)$, CURVE (d₁) AND (d₂)

$\lambda_c = f_n(br/gK_g)$ CURVE (e)

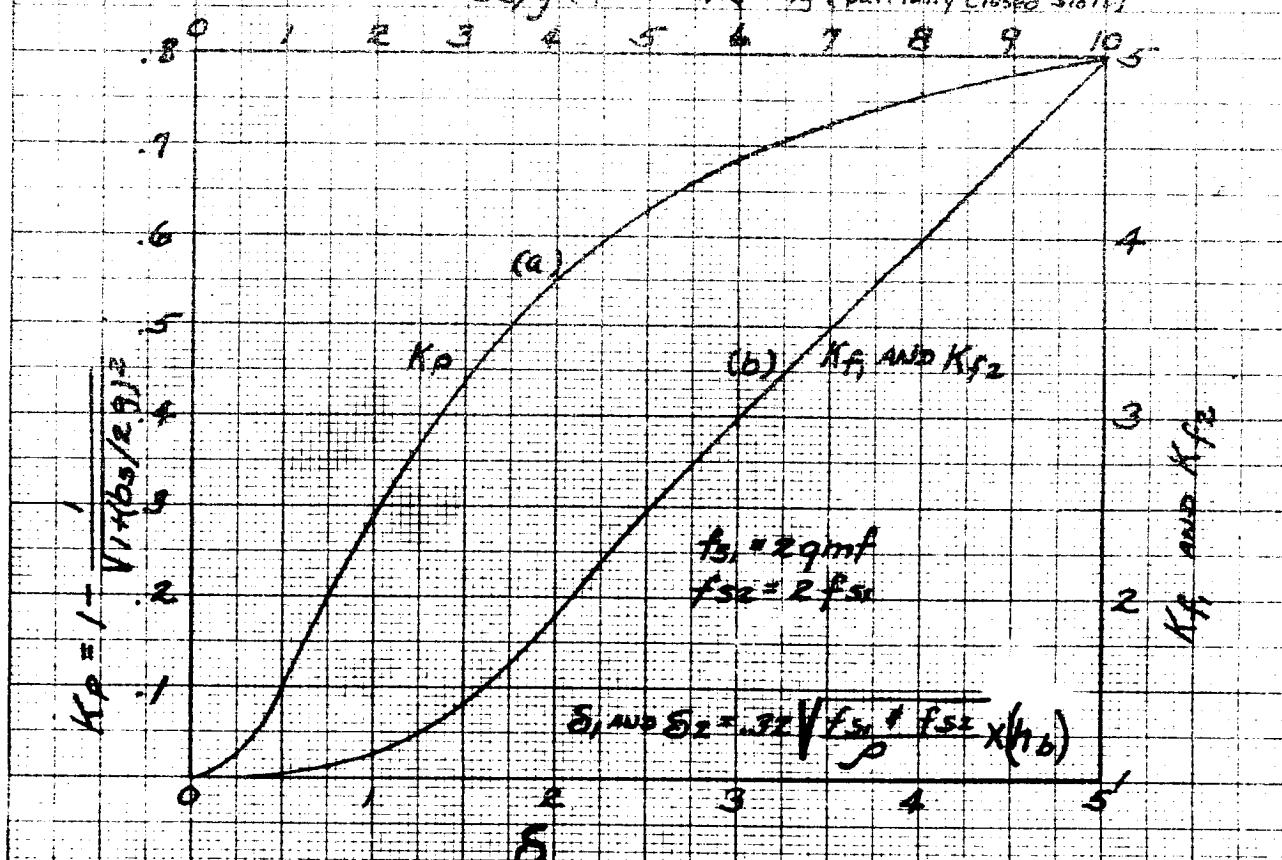
B_g IS IN KILOLINES PER SQ. INCH



$$\lambda_c = \frac{.75}{K_p} \quad (\text{FOR ROUND OR SQ.-bars})$$

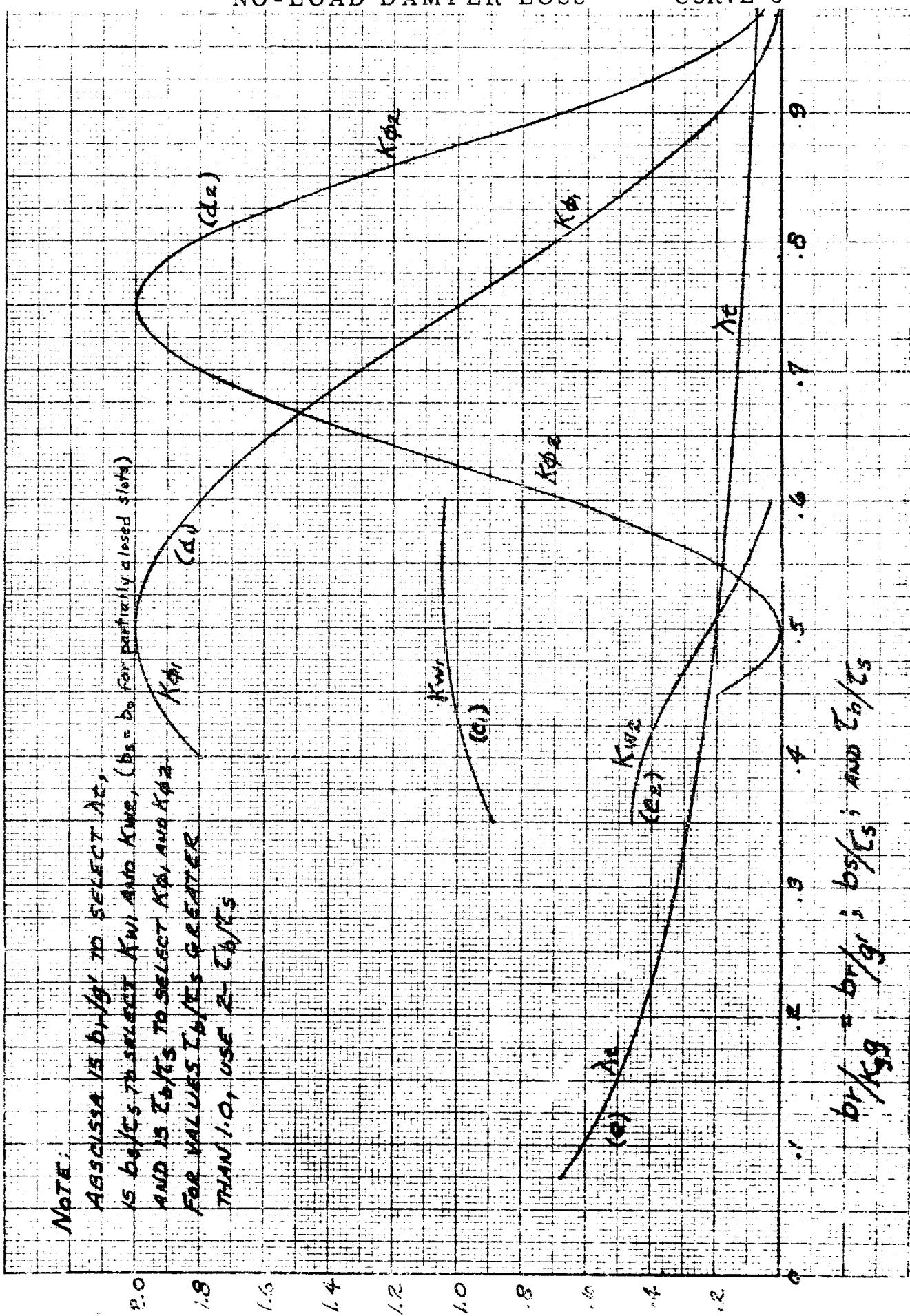
$$\lambda_c = \frac{b_b}{3bb' K_p} \quad (\text{FOR RECT. BARS})$$

b_s/g (open slots) & b_s/g' (partially closed slots)



From E. I. Pollard "Calculation of No-Load Damper Winding Loss in Synchronous Machines", AIEE Vol. 51, 1932, pp 477-81.

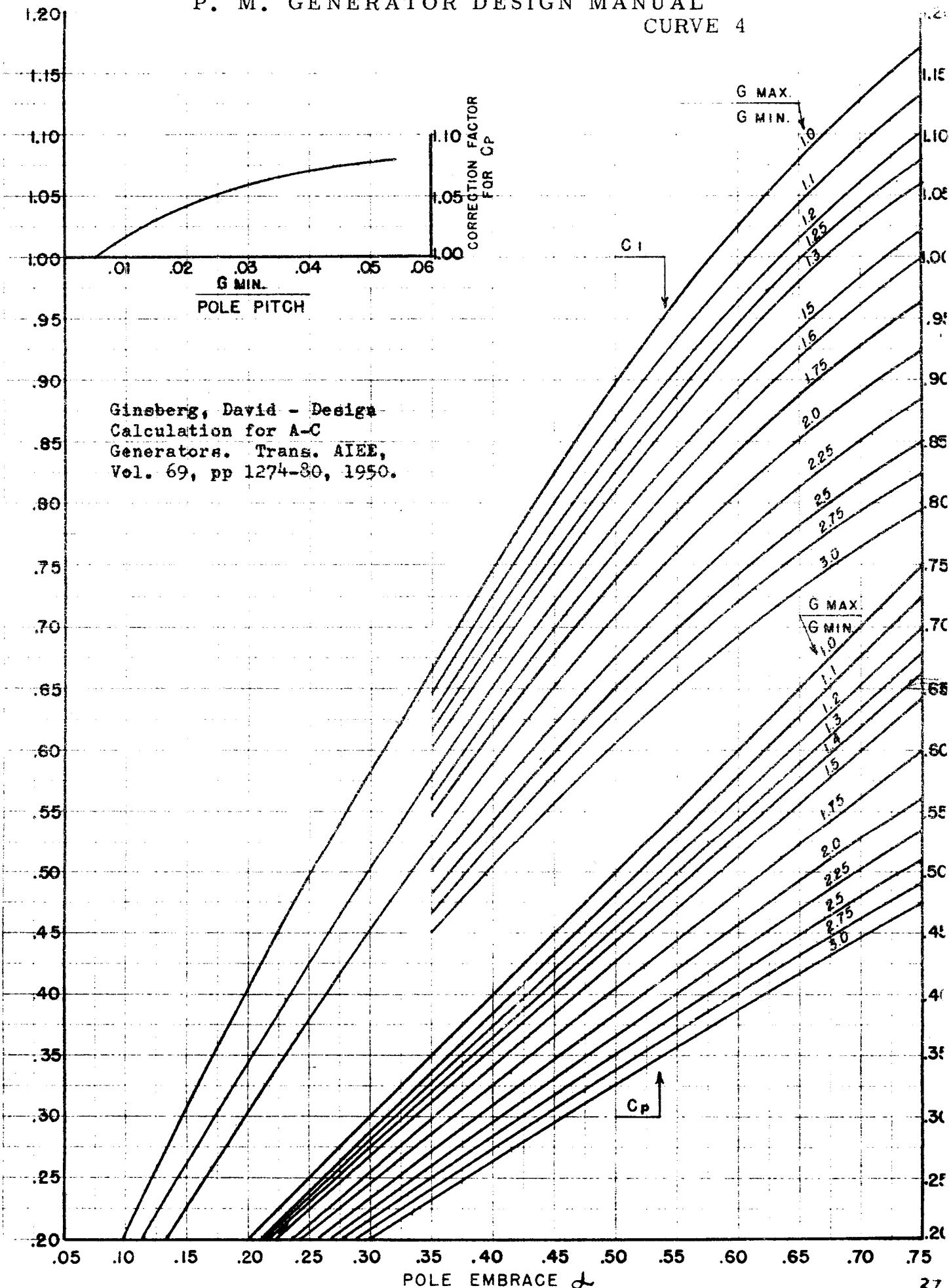
P. M. GENERATOR DESIGN MANUAL
NO-LOAD DAMPER LOSS CURVE 8



$b_1/k_1 = b_1/k_1'; b_1/k_1'; \text{ and } b_1/k_1''$

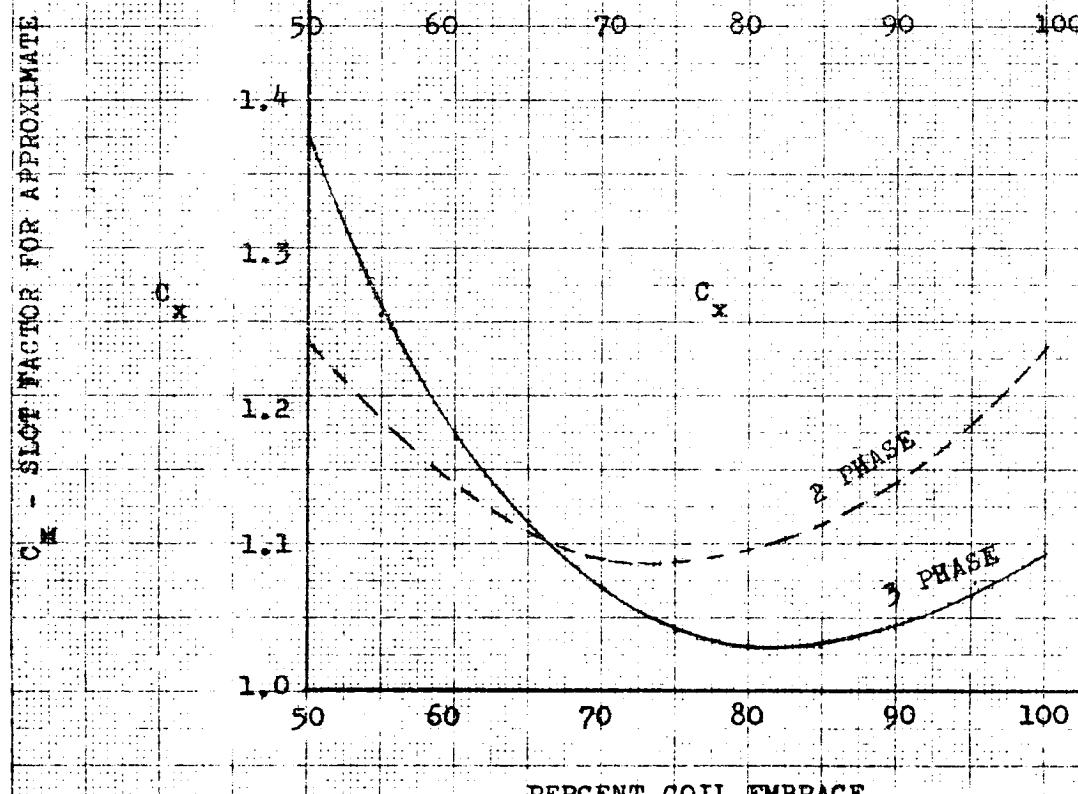
P. M. GENERATOR DESIGN MANUAL
CURVE 4

63



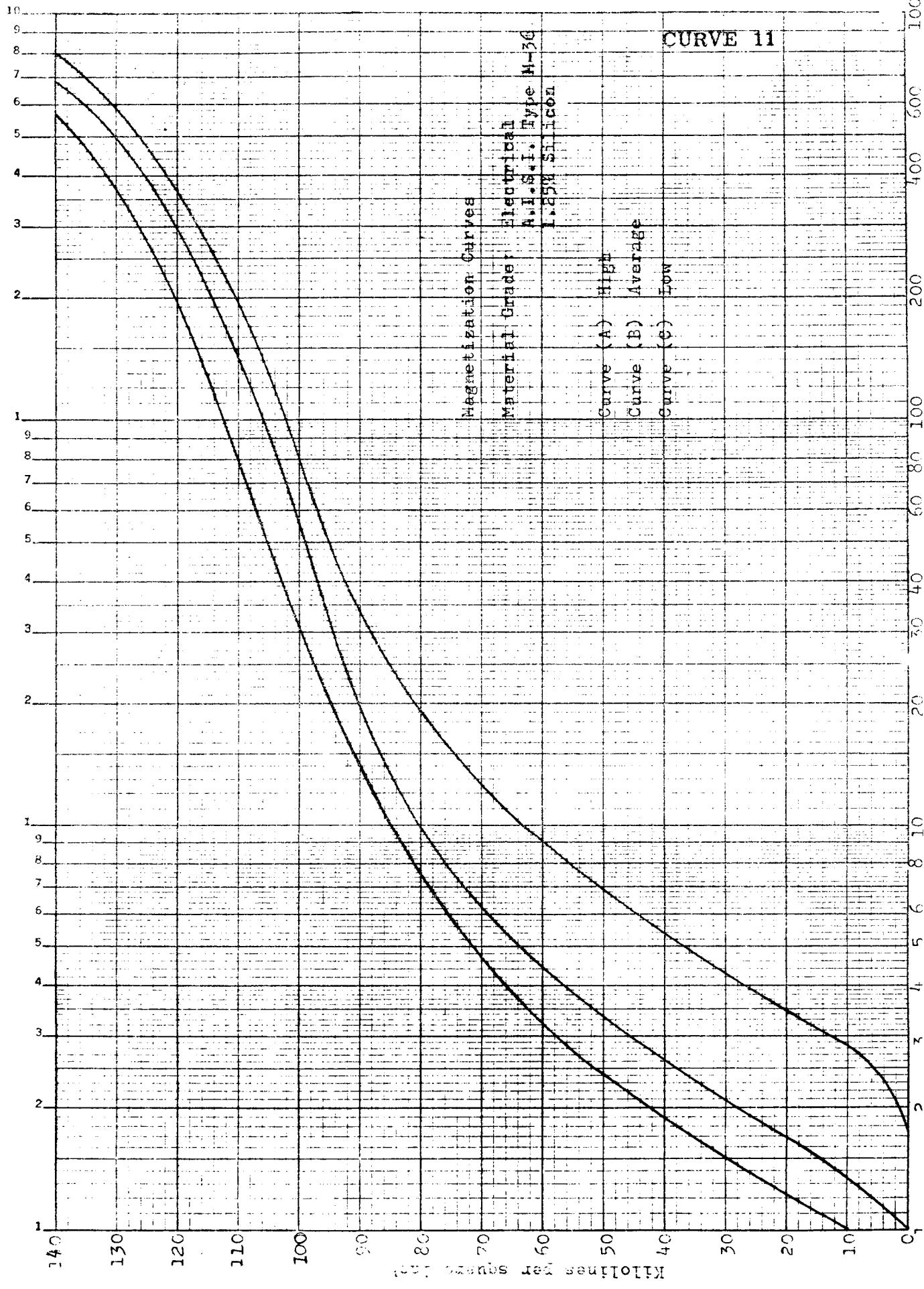
CURVE 5

PERCENT COIL EMBRACE

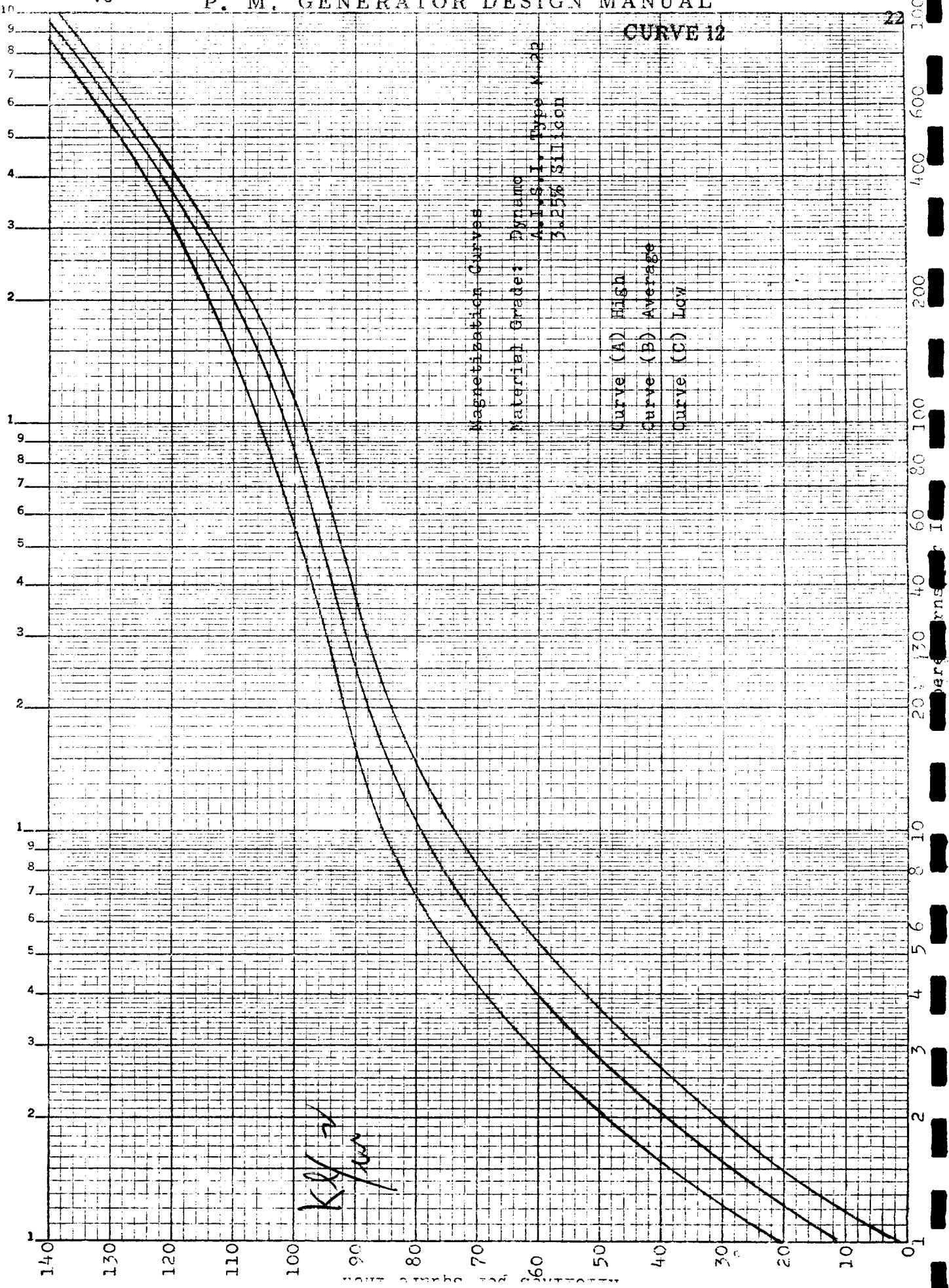
C_s - SLOP FACTOR FOR APPROXIMATE REACTANCE FORMULA

K4
10 X 10 TO THE CM. 359.14
KELFEL & ESTER CO. PATENTED

K.E. SEMI-LOGARITHMIC
KELVIN & LEHRER CO.
3 CYCLES - 70 H.P. - 1200 RPM.

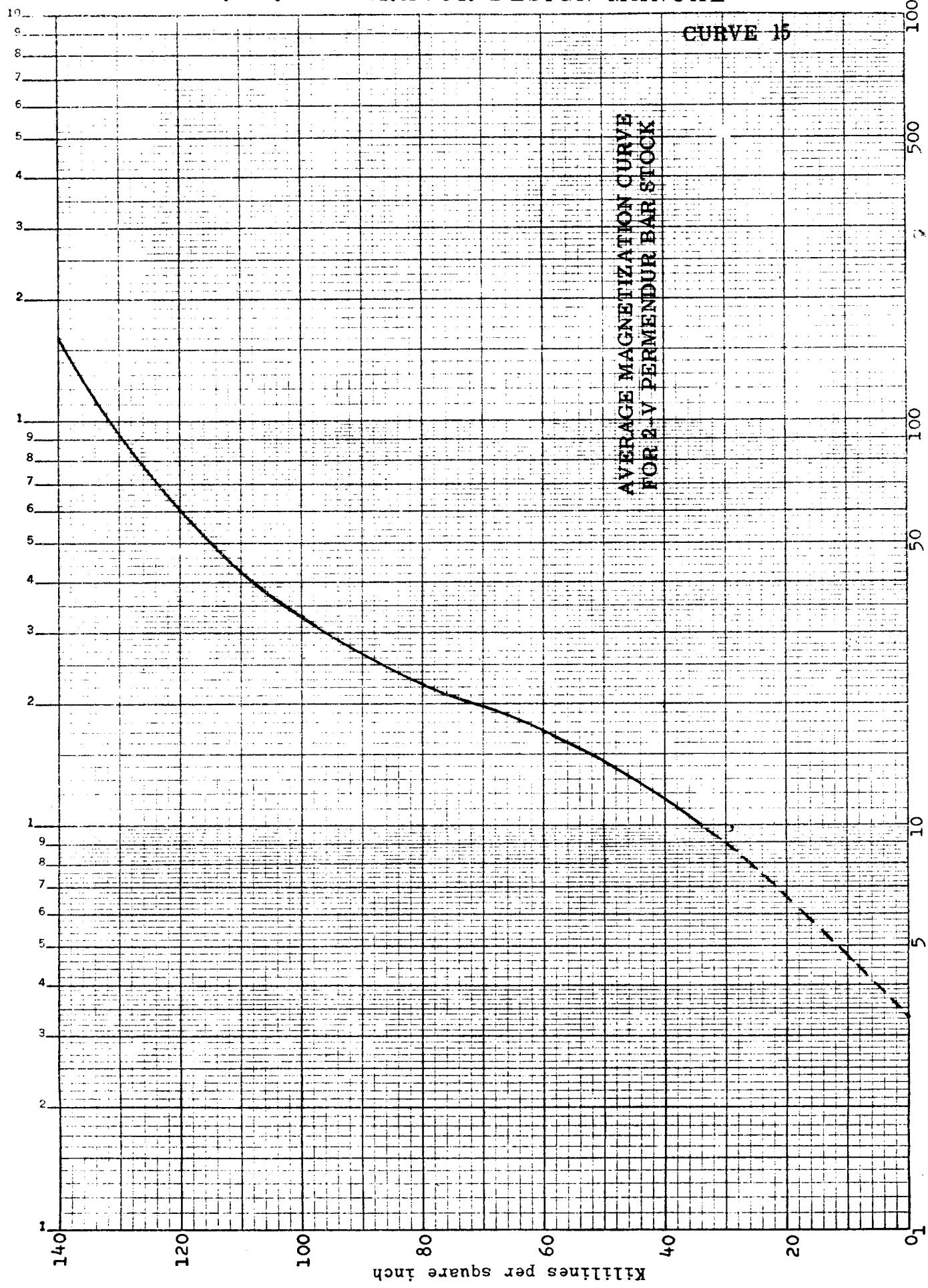


CURVE 12

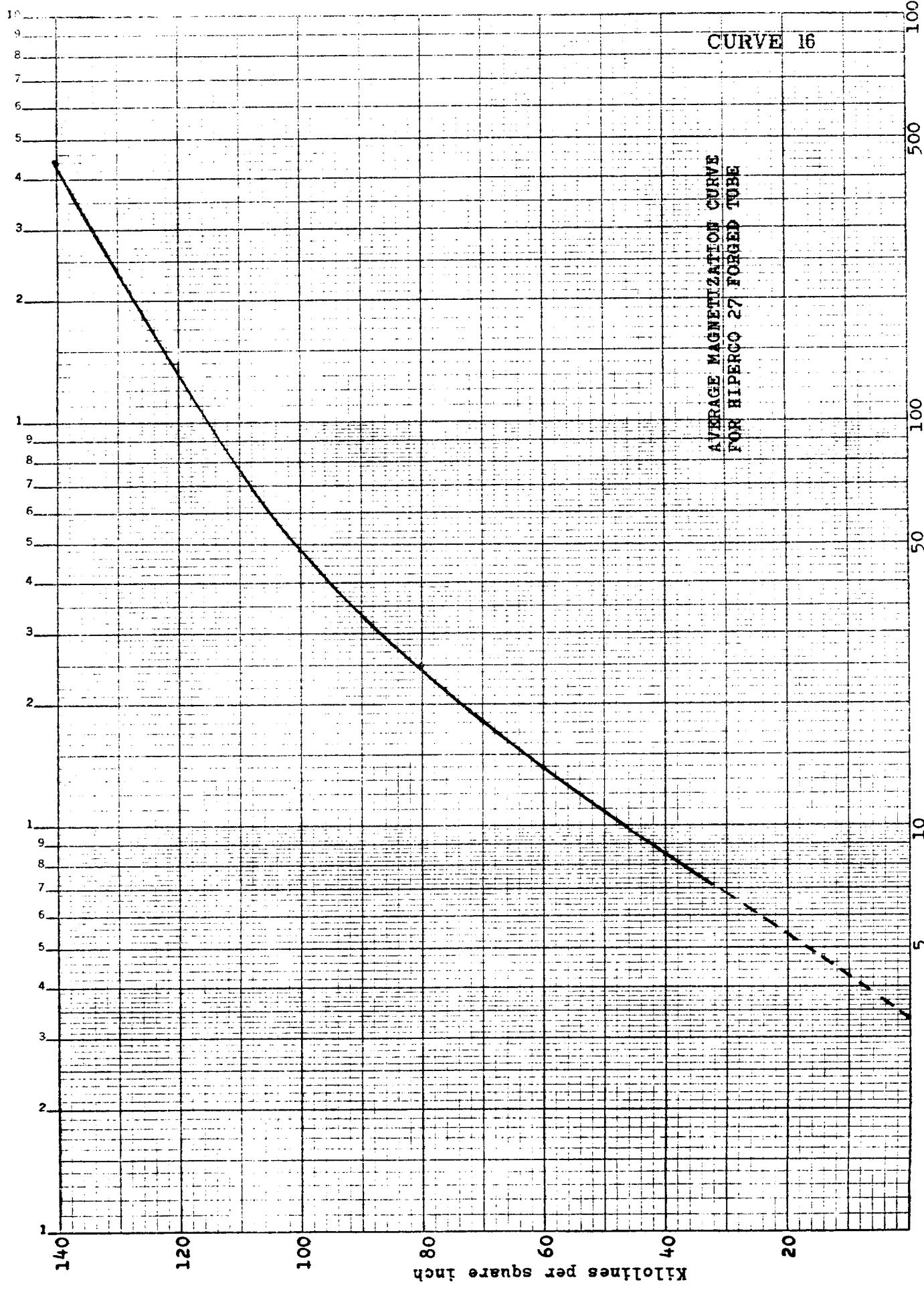


Amperes Turns per Inch

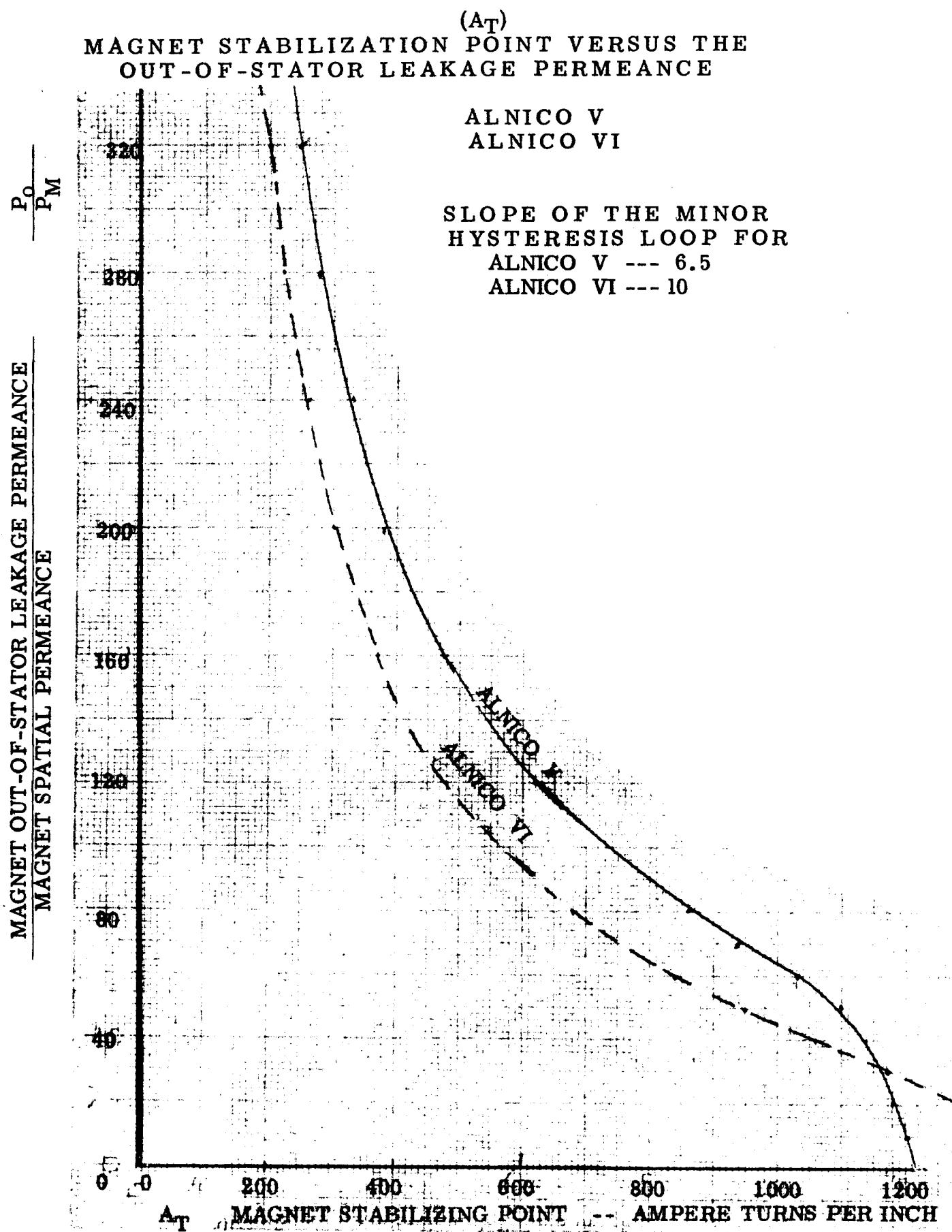
 SEMILOGARITHMIC
KELF & LESSER CO. WATKINS,
A CYCLES X 70 DIVISIONS



K&E SEMI-LOGARITHMIC
KCUFT FIELD & ESCR CC
3 CYCLES X 70 DIVISIONS



CURVE 17



CURVE 18

(AT)

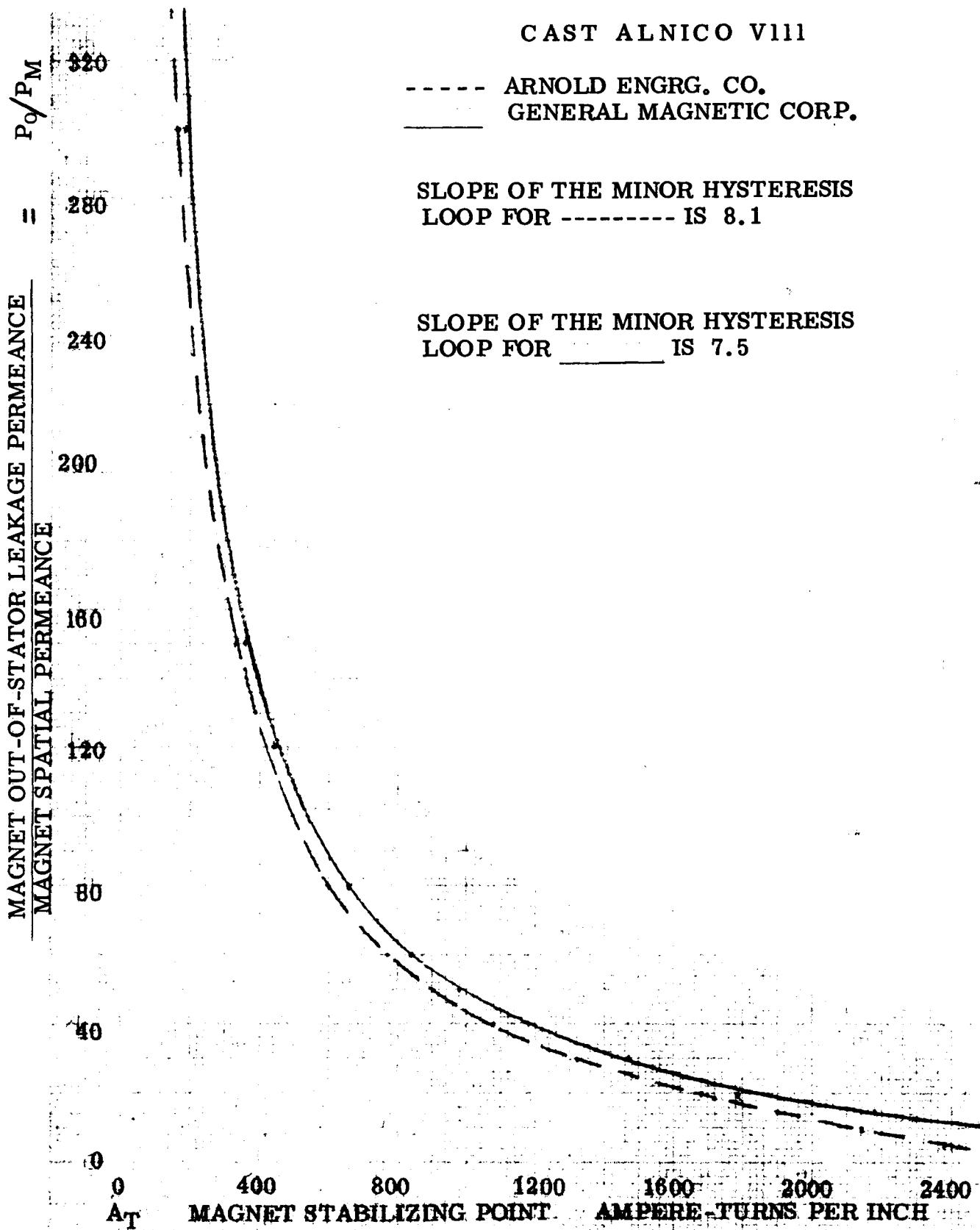
MAGNET STABILIZATION POINT VERSUS
OUT-OF-STATOR LEAKAGE PERMEANCE

CAST ALNICO V111

— ARNOLD ENGRG. CO.
— GENERAL MAGNETIC CORP.

SLOPE OF THE MINOR HYSTERESIS
LOOP FOR ----- IS 8.1

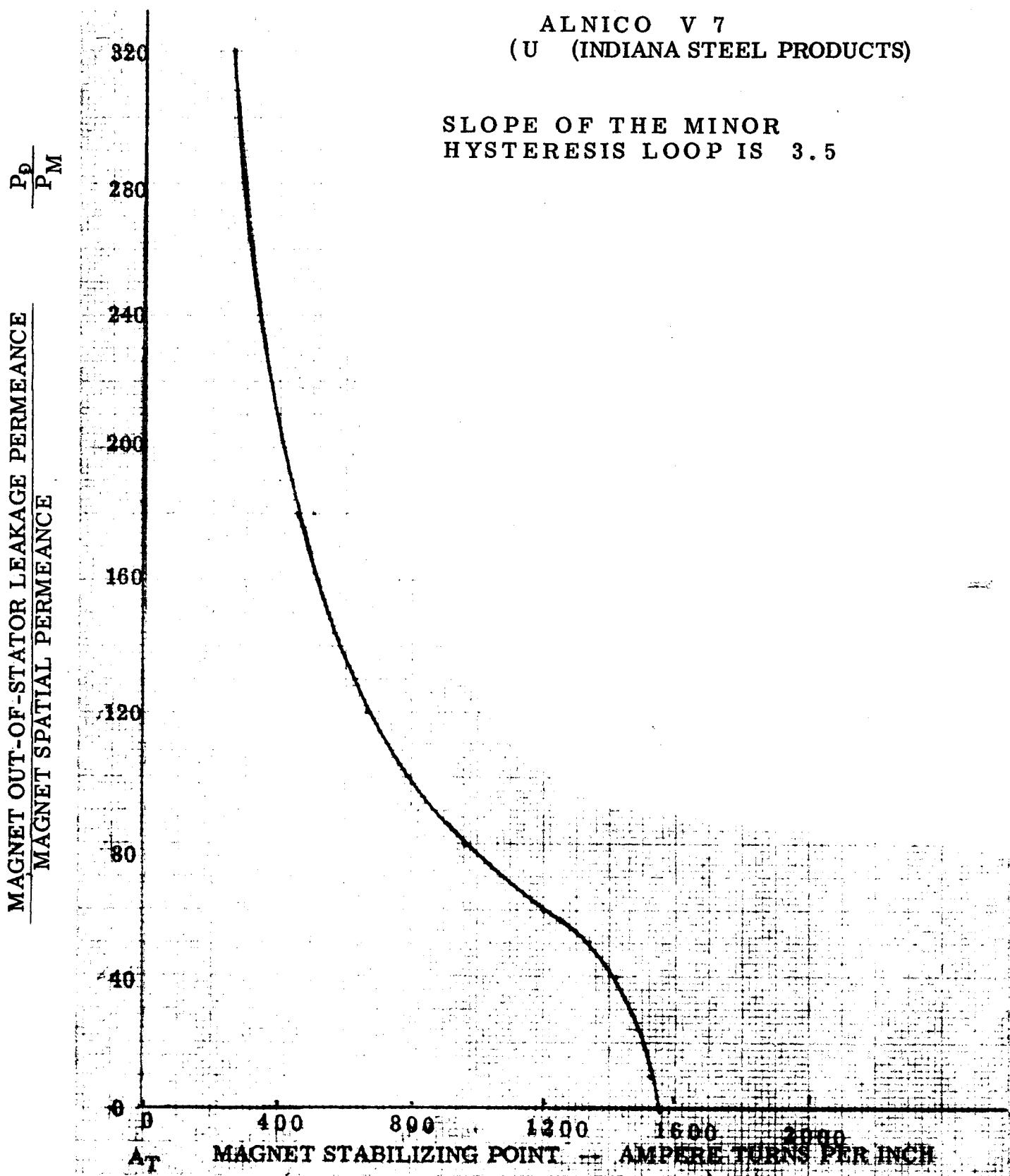
SLOPE OF THE MINOR HYSTERESIS
LOOP FOR — IS 7.5



P. M. GENERATOR DESIGN MANUAL

(A_T)

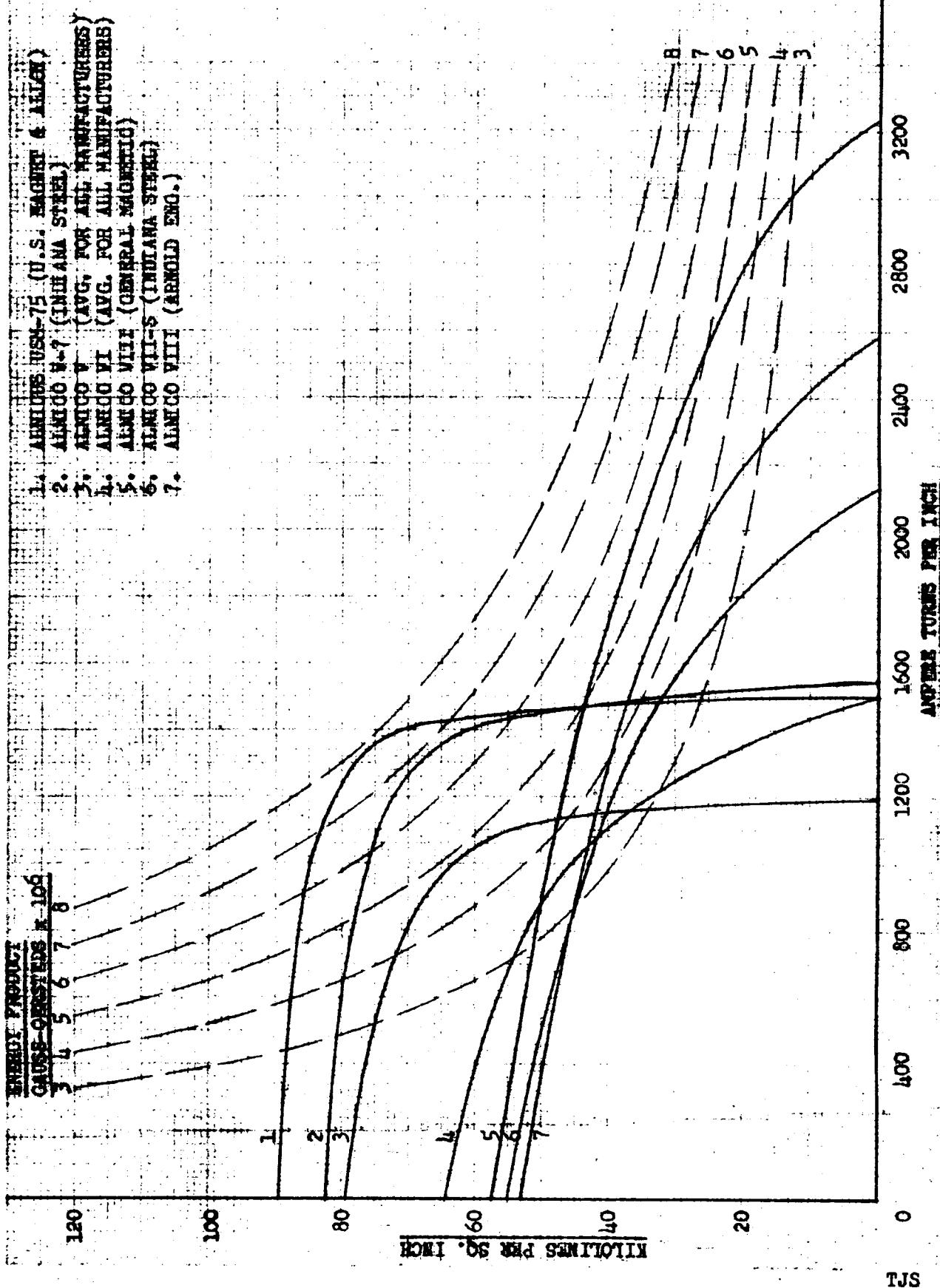
CURVE 19

MAGNET STABILIZATION POINT VERSUS
OUT-OF-STATOR LEAKAGE PERMEANCEALNICO V 7
(U (INDIANA STEEL PRODUCTS))SLOPE OF THE MINOR
HYSTERESIS LOOP IS 3.5

DEMAGNETIZATION CURVES FOR HIGH ENERGY
PRODUCT CAST ALNICO'S

1-2-63

CURVE 20



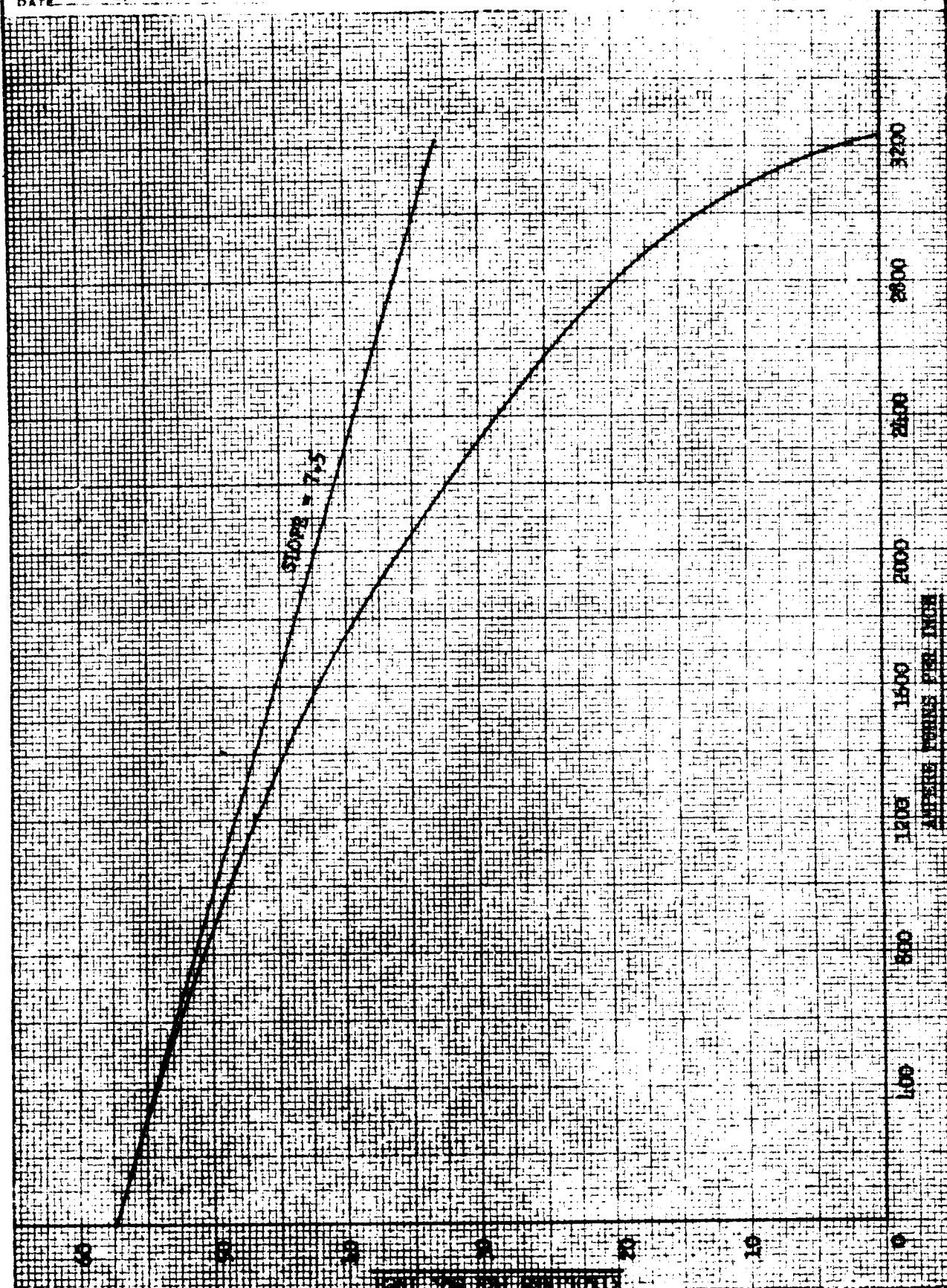
GRAPH NO. _____

SHOWING _____

DEMAGNETIZATION CURVE FOR CAST ALNICO VIII
(GENERAL MAGNETIC CORP.)

CURVE 21

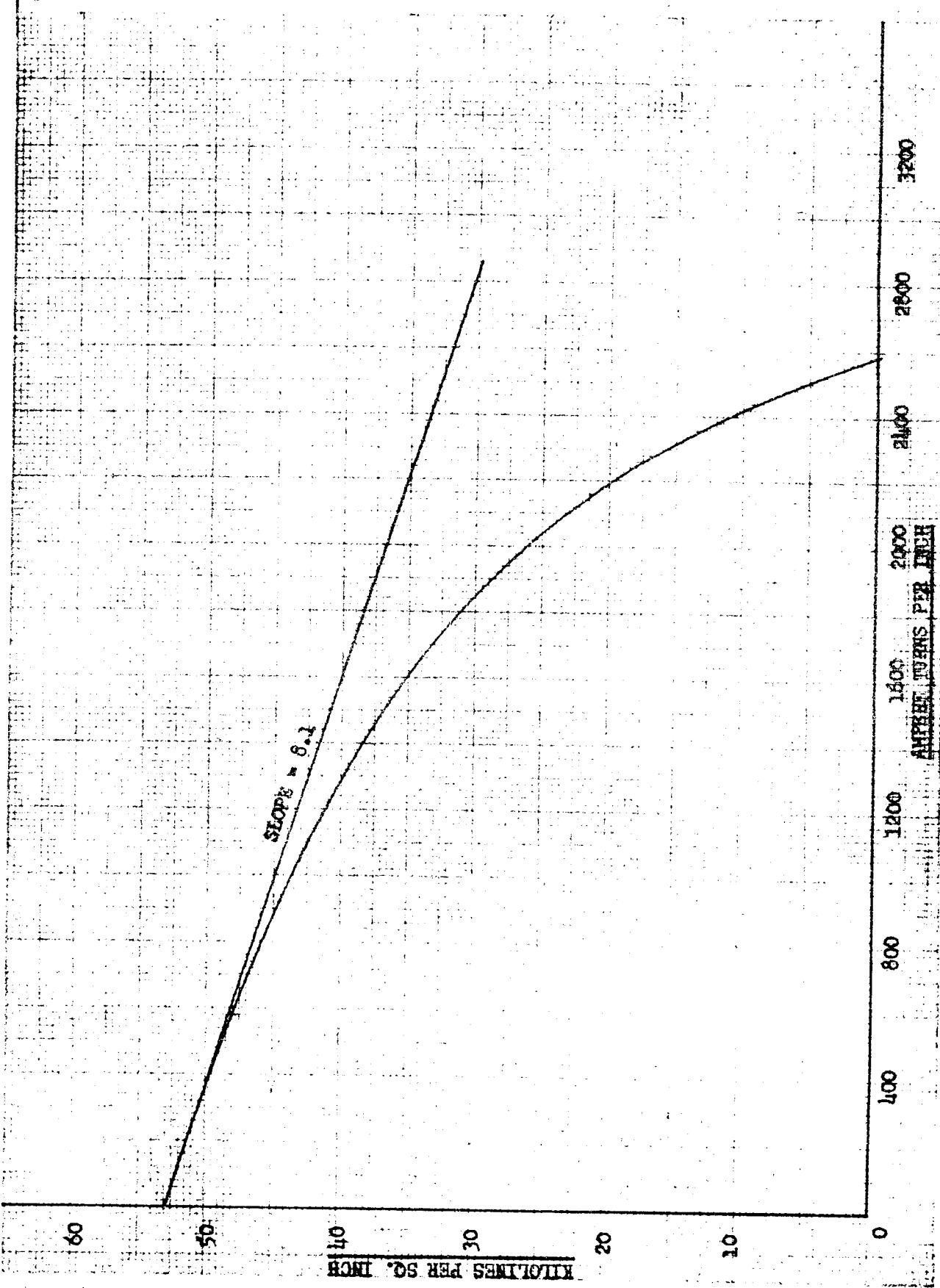
DATE 12-19-62



DEMAGNETIZATION CURVE FOR CAST ALNICO VIII
(ARNOLD ENGINEERING CO.)

12-19-62

CURVE 22



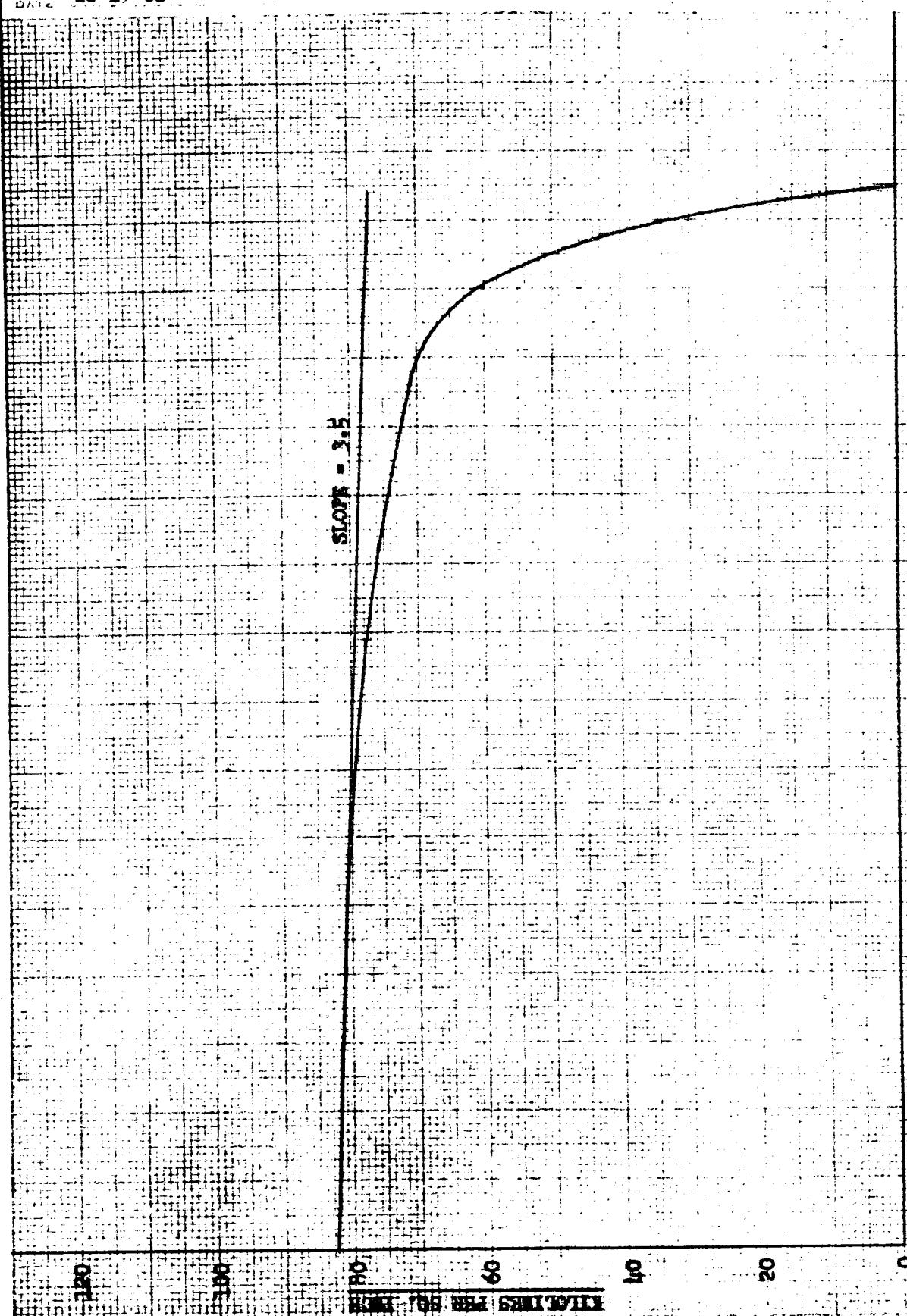
GRAPH NO.

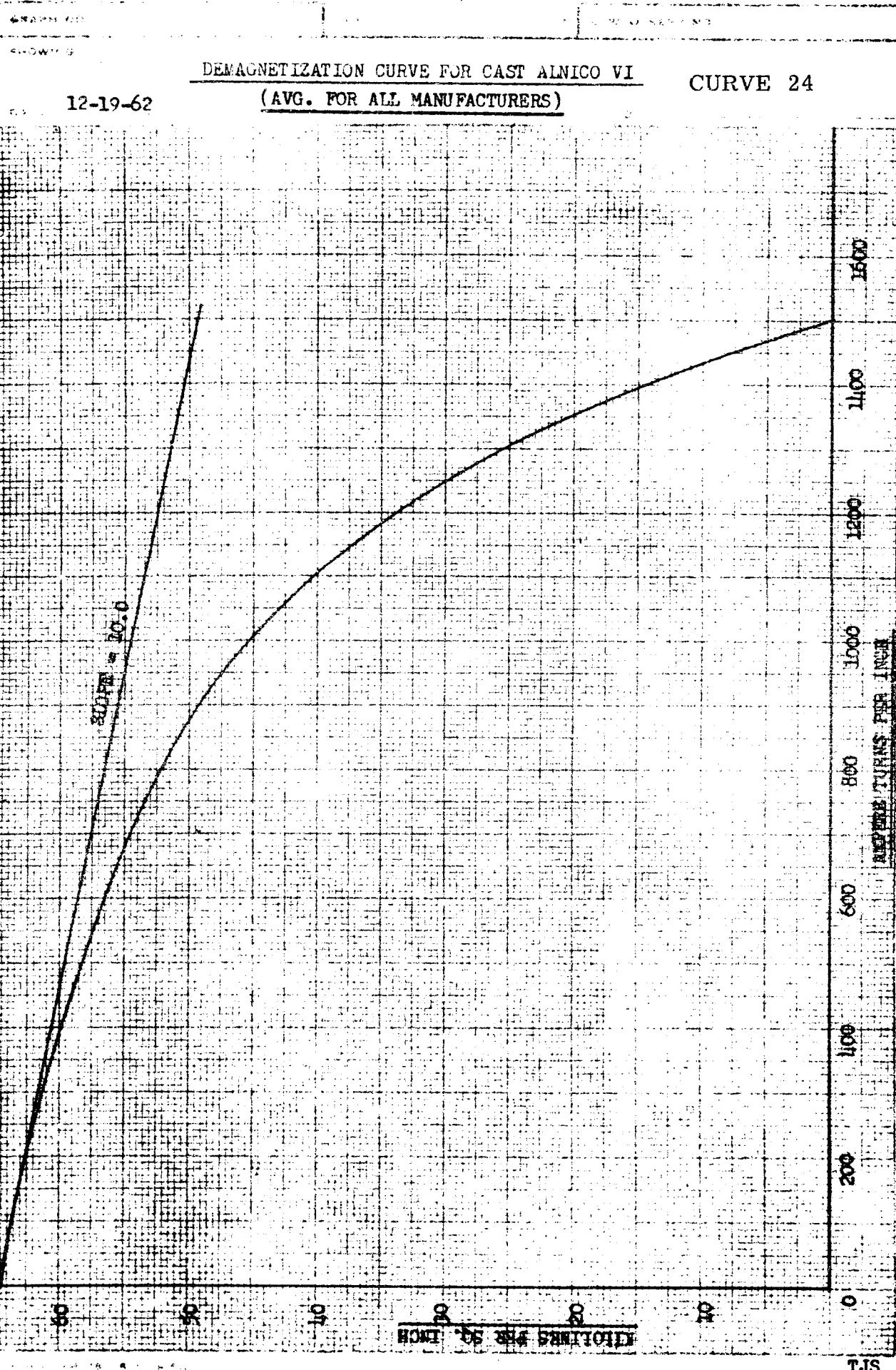
SHOWING

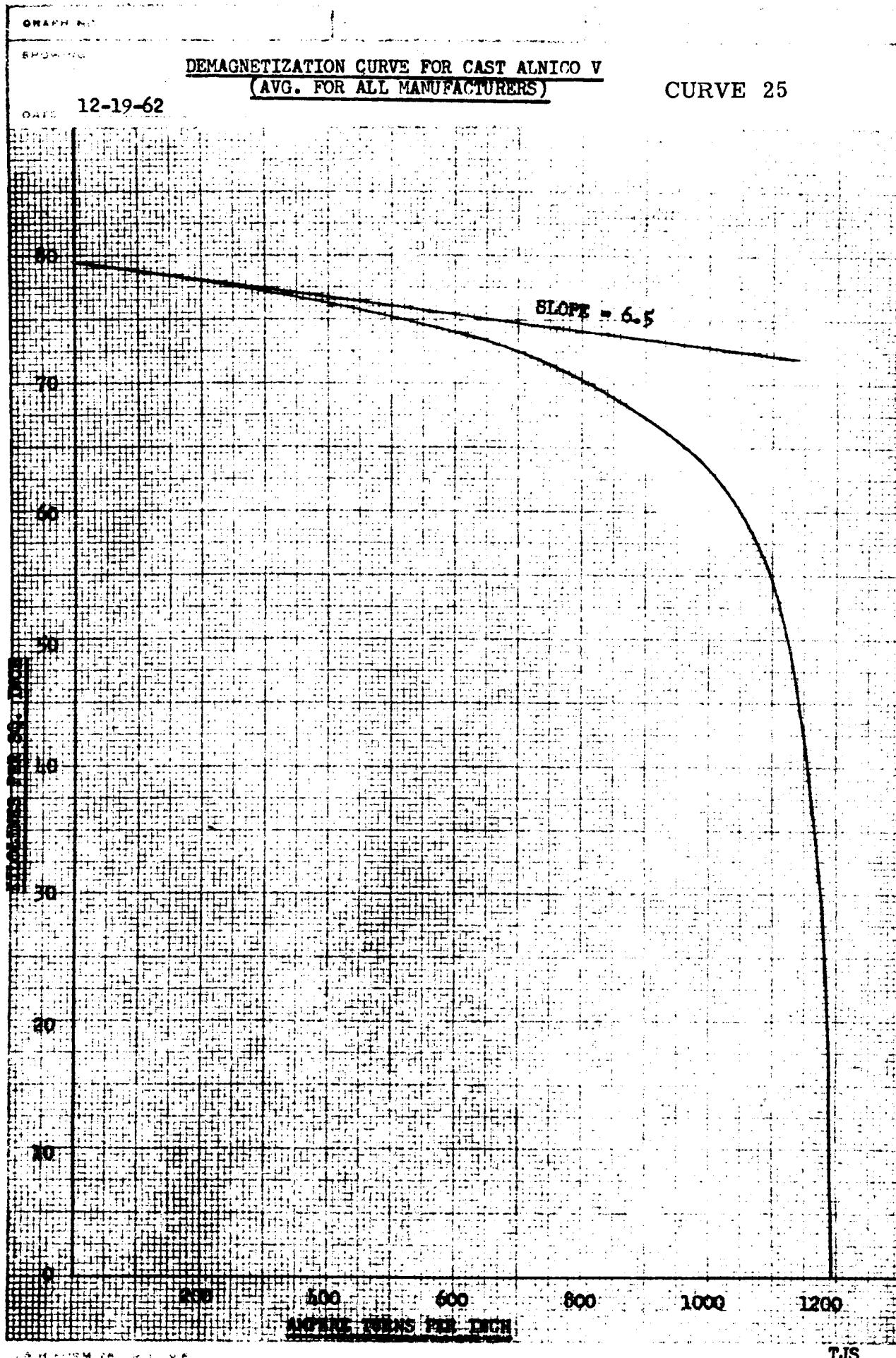
DEMAGNETIZATION CURVE FOR CAST ALNICO V-7
(INDIANA STEEL PRODUCTS)

CURVE 23

DATE 12-19-62



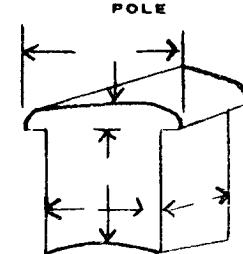




P. M. GENERATOR DESIGN MANUAL

<u>Calculation Location</u>	<u>Symbol -</u>	<u>Explanation</u>
(78)	A	Ampere conductors per inch of stator periphery
	α_1	Chordal distance between outer edges of adjacent pole magnets.
	α_2	Chordal distance between inboard edges of adjacent pole magnets.
	A_T	Magnet stabilizing point. The ampere turn value at intersection of $\frac{P_o}{P_m}$ shear line with the major hysteresis loop.
(46)	a_c	Strand area (stator)
(89)	a_{cf}	Field conductor area
(85)	a_p	Pole area
(20)	B	Density
(128)	B_c	Core Density
(125)	B_g	Gap density
(140)	B_p	Pole density no load
(127)	B_T	Tooth density
(89)	b_{bo}	Width of slot opening (damper)
(89)	b_{bl}	Width of rectangular slot (damper)

P. M. GENERATOR DESIGN SHEET

STATOR		ROTOR		
PUNCHING I. D.		SINGLE GAP	Ge	
PUNCHING O. D.		ROTOR DIAMETER		
CORE LENGTH		PERIPHERAL SPEED		
DBS x 2		POLE PITCH	α	
SLOTS		POLE AREA		
SIZE SLOTS		MAGNET		
CARTER COEFF.		<i>Bm</i>		
TYPE WDG.				
THROW				
SKEW & DIST. FACT.				
CHORD FACT				
COND. PER SLOT		NO. DAMPER BARS		
TOTAL EFF. COND.		BAR SIZE		
COND. SIZE		BAR PITCH	hbo bbo	
COND. AREA				
CURRENT DENSITY				
WDG. CONST.	C1			
TOTAL FLUX				
GAP AREA				
GAP DENSITY				
POLE CONST.				
FLUX PER POLE				
TOOTH PITCH				
TOOTH DENSITY				
CORE DENSITY				
GRADE OF IRON				
% MEAN TURN				
RES. PER PH. •	0			
EDDY FACT. TOP				
EDDY FACT. BOT.				
DEMAG. FACT. Cm	Cq			
AMP. COND. PER IN.				
REACT. FACTOR				
COND. PERM.				
END PERM.				
LEAKAGE REACT.				
AIR GAP PERM.				
REACT. OF ARM Xad	Xaq			
WT. OF COPPER				
WT. OF IRON				
		AIR GAP A. T		
		SHORT CIRC. RATIO		
		LOSSES-EFFICIENCY		
		% LOAD		
		F & W		
		STA. TEETH		
		STA. CORE		
		POLE FACE		
		DAMPER		
		STA I ² R		
		EDDY		
		E LOSSES		
		RATING		
		RTG+LOSS		
		SYNCH. Xd	Xq	
		UNSAT TRANS.		
		SAT. TRANS.		
		SUBTRANS. Xd	Xq	
		NEG. SEQUENCE		
		ZERO SEQUENCE		
		OPEN CIRC. TIME CON.		
		ARM TIME CON.		
		TRANS. TIME CON.		
		SUBTRANS. TIME CON.		
MODEL NO. _____ TYPE COOLING _____				
KVA	% PF	VOLTS	AMPS	
PH.	~	RPM		



P.M. GENERATOR DESIGN MANUAL

Calculation Location	Symbol	Explanation
(76)	b_h	Pole head width
(22)	b_o	Width of slot opening (stator)
(76)	b_p	Pole body width
(22)	b_s	Stator slot dimension per Fig. 1
(15)	b_v	Width of duct
(22)	b_1	Stator slot dimensions per Fig. 1
(22)	b_2	
(22)	b_3	
(74)	C_m	Demagnetizing factor
(73)	C_p	Average/maximum field form
(75)	C_q	Cross magnetization factor
(72)	C_w	Winding constant
(71)	C_1	Ratio max. to fund
(32)	c	Parallel circuits
(12)	D	Stator outside diameter
(11)	d	Stator inside diameter
(35)	d_b	Diameter of bender pin
(11a)	d_r	Rotor outside diameter
(3)	E	Line volts
	E_{NL}	Line-to-line terminal volts at no load, rated speed

P.M. GENERATOR DESIGN MANUAL

<u>Calculation Location</u>	<u>Symbol</u>	<u>Explanation</u>
	E_{FL}	Line-to-line terminal volts at full load current, rated speed
(4)	E_{PH}	Phase volts
(55)	$E_{F \text{ top}}$	Eddy factor top
(56)	$E_{F \text{ bot}}$	Eddy factor bottom
(130)	F_c	Stator core ampere turns
(131)	F_g	Air gap ampere turns.
(129)	F_t	Stator tooth ampere turns
(147)	$F\&W$	Friction and windage
(5a)	f	Frequency
(69)	g_e	Effective air gap
(59a)	g_{\max}	Maximum air gap
	h	Average slope of the minor hysteresis loop
(22)	h_0	Stator slot dimension
(22)	h_1	
(22)	h_2	
(22)	h_3	
(22)	h_s	
(22)	h_t	
(22)	h_w	

P. M. GENERATOR DESIGN MANUAL

<u>Calculation Location</u>	<u>Symbol</u>	<u>Explanation</u>
(89)	h_{bo}	Height of slot opening
(89)	h_{bl}	Rectangular bar thickness
(24)	h_c	Depth below slot
(76)	h_p	The pole body height (magnet length)
(76)	h_h	Pole head height
(37)	h_{st}	Uninsulated strand height
(38)	h'_{st}	Distance between center line of strands
(8)	I_{PH}	Phase current
	I_{SC}	Short circuit current per terminal when all phases are solidly shorted at rated speed.
(158)	$I^2 R_S$	Stator copper loss
(9a)	K_c	Adjustment factor
(43)	K_d	Distribution factor
(18)	K_i	Stacking factor
(44)	K_p	Pitch factor
(67)	K_s	Carter coefficient
(42)	K_{SK}	Skew factor
(2)	KVA	Machine rating

P. M. GENERATOR DESIGN MANUAL

<u>Calculation Location</u>	<u>Symbol</u>	<u>Explanation</u>
(151)	K_1	Pole face loss factor
(19)	k	Watts per lb.
(48)	L_E	End extension one turn
(113)	L_F	Field self-inductance
(13)	ℓ	Gross core length
(93)	ℓ_b	Damper bar length
(136)	ℓ_{e2}	Coil extension straight portion
(76)	ℓ_n	Pole head length
(76)	ℓ_p	Pole body length
(17)	ℓ_s	Solid core length
(49)	ℓ_t	1/2 mean turn
(100)	ℓ_{tr}	Mean length of field turns
(5)	m	Number of phases
(34)	N_{st}	Strands per conductor
(92)	n_b	Number of damper bars
(45)	n_e	Effective conductors
(30)	n_s	Conductor per slot
(14)	n_v	Number of ducts
(9)	P. F.	Power factor
(6)	p	Number of poles

P. M. GENERATOR DESIGN MANUAL

<u>Calculation Location</u>	<u>Symbol</u>	<u>Explanation</u>
	P_1	Permeance of the flux leakage path from pole side to pole side.
	P_2	Permeance of the flux leakage paths from pole head surface to pole head surface plus the permeance of the flux leakage path between the two adjacent pole head edges.
	P_3	Permeance of the flux leakage path between the ends of adjacent pole magnets.
	P_{s1}	Permeance of the non-useful leakage flux path between pole head edges or between pole head underside.
	P_{s2}	Permeance of the flux leakage path between end surfaces of the pole heads.
	P_m	Magnet spatial permeance.
	P_i	Total permeance of the rotor, in-stator flux leakage paths.
	P_o	Total permeance of the rotor, out-of-stator flux leakage paths.
	P_g	Permeance of the main air gap
	P_w	Total apparent permeance of the working air gap.

P. M. GENERATOR DESIGN MANUAL

<u>Calculation Location</u>	<u>Symbol</u>	<u>Explanation</u>
(23)	Q	Number of slots
(53)	R _{ph} (cold)	Stator resistance at 20°C
(54)	R _{ph} (hot)	Stator resistance at X°C
(47)	s _s	Stator current density
(133)	T _a	Armature time constant
(134)	T' _d	Transient time constant
(135)	T'' _d	Subtransient time constant
(132)	T' _{do}	Open circuit time constant
(149)	W _c	Stator core loss
(172)	W _{DFL}	Damper loss at full load
(157)	W _{DNL}	Damper loss at no load
(171)	W _{PFL}	Pole face losses at full load
(150)	W _{PNL}	Pole face loss at no load
(170)	W _{TFL}	Stator tooth loss at full load
(148)	W _{TNL}	Stator tooth loss at no load
(98a)	V _r	Peripheral speed of rotor
(79)	X	Reactance factor
(81)	X _{ad}	Reactance direct axis
(82)	X _{aq}	Reactance quadrature axis
(83)	X _d	Synchronous reactance direct axis
(119)	X' _d	Stator transient reactance

P. M. GENERATOR DESIGN MANUAL

Calculation Location	Symbol	Explanation
(120)	X_d''	Subtransient reactance direct axis
(115)	X_{Dd}	Leakage reactance direct axis
(117)	X_{Dq}	Leakage reactance quadrature axis
(118)	X'_{du}	Unsaturated transient reactance
(80)	X	Leakage
(84)	X_q	Synchronous reactance quadrature axis
(121)	X''_q	Subtransient reactance quadrature axis
(123)	X_0	Zero sequence reactance
(122)	X_2	Negative sequence reactance
(96)	$X_D^{\circ C}$	Expected damper bar $^{\circ C}$
(50)	$X_S^{\circ C}$	Expected temp. stator in $^{\circ C}$
(95)	ρ_D	Resistivity of damper bar at $20^{\circ C}$
(51)	ρ_S	Resistivity of stator cond. at $20^{\circ C}$
(104)	ρ_F	Resistivity of field conductor
(138)	ϕ_L	Leakage flux at no load
(160)	ϕ_{LL}	Leakage flux at full load
(126)	ϕ_P	Flux per pole
(139)	ϕ_{PT}	Total flux per pole at no load
(124)	ϕ_T	Total fluc
(94)	τ_b	Damper bar pitch

P. M. GENERATOR DESIGN MANUAL

<u>Calculation Location</u>	<u>Symbol</u>	<u>Explanation</u>
(41)	τ_p	Pole pitch
(26)	τ_s	Slot pitch
(27)	$\tau_{s \ 1/3}$	Slot pitch 1/3 distance from narrowest point
(40)	τ_{sk}	Stator slot skew
(70)	λ_a	Air gap permeance
(63)	λ_E	End permeance
(62)	λ_i	Stator conductor permeance

P. M. GENERATOR DESIGN MANUAL

(1)	--	<u>DESIGN NUMBER</u> - To be used for filing purposes
(2)	KVA	<u>GENERATOR KVA</u>
(3)	E	<u>LINE VOLTS</u>
(4)	E_{PH}	<u>PHASE VOLTS</u> - For 3 phase, delta connected generator $E_{PH} = \frac{(\text{Line Volts})}{\sqrt{3}} = \frac{(3)}{\sqrt{3}}$ For 3 phase, wye connected generator $E_{PH} = (\text{Line Volts}) = (3)$
(5)	m	<u>PHASES</u> - Number of
(5a)	f	<u>FREQUENCY</u> - In cycles per second
(6)	P	<u>POLES</u> - Number of
(7)	RPM	<u>SPEED</u> - In revolutions per minute
(8)	I_{PH}	<u>PHASE CURRENT</u> - In amperes at rated load
(9)	P.F.	<u>POWER FACTOR</u> - Given in per unit

(11)	d	<u>STATOR PUNCHING I. D.</u> - The inside diameter of the stator punching in inches
(11a)	d_r	<u>ROTOR PUNCHING O. D.</u> - The outside diameter of the rotor punching in inches
(12)	D	<u>PUNCHING O. D.</u> - The outside diameter of the stator punching in inches
(13)	ℓ	<u>GROSS CORE LENGTH</u> - In inches
(14)	n_v	<u>RADIAL DUCTS</u> - Number of
(15)	b_v	<u>RADIAL DUCT WIDTH</u> - In inches
(16)	K_i	<u>STACKING FACTOR</u> - This factor allows for the coating (core plating) on the punchings, the burrs due to slotting, and the deviations in flatness. Approximate values of K_i are given in Table IV.

THICKNESS OF LAMINATIONS (INCHES)	GAGE	K _i
.014	29	0.92
.018	26	0.93
.025	24	0.95
.028	23	0.97
.063	--	0.98
.125	--	0.99

TABLE IV

- (17) ℓ_s SOLID CORE LENGTH - The solid length is the gross length times the stacking factor. If ventilating ducts are used, their length must be subtracted from the gross length also.

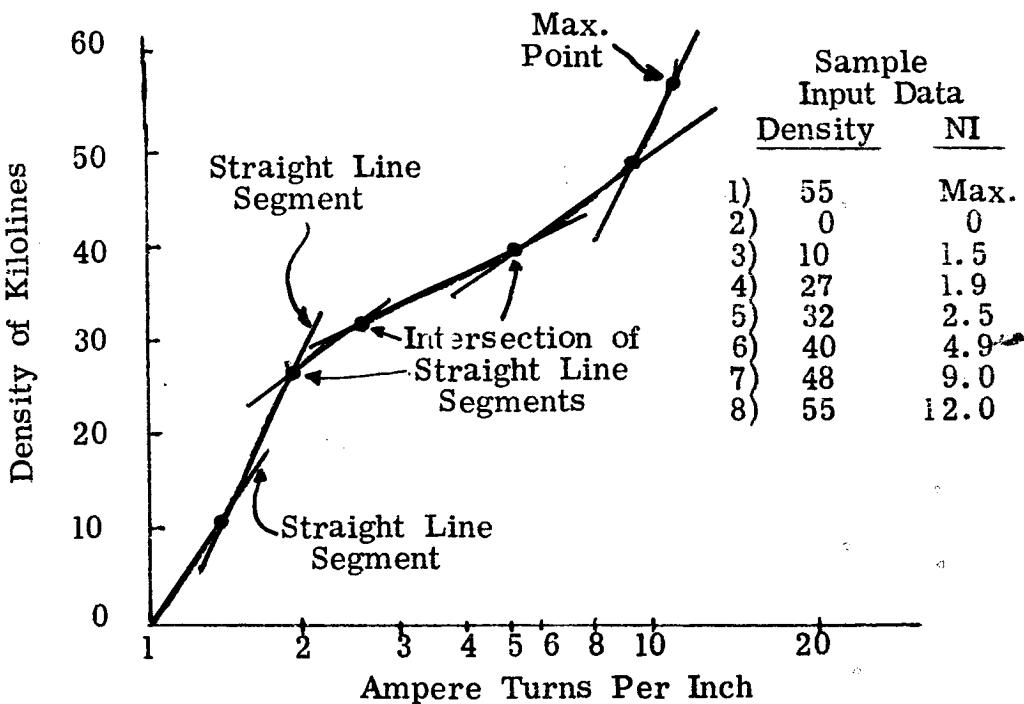
$$\ell_s = (K_i) \left[(\ell) - (n_v) (b_v) \right] = (16) \left[(13) - (14) (15) \right]$$

- (18) MATERIAL - This input is used in selecting the proper magnetization curves for stator, yoke; pole; and shaft; when different materials are used. Separate spaces are provided on the input sheet for each section mentioned above. Where curves are available on card decks, used the proper identifying code. Where card decks are not available submit data in the following manner:

The magnetization curve must be available on semi-log paper. Typical curves are shown in this manual on Curves 15 and 16. Draw straight line segments through the curve starting with zero density. Record the coordinates of the points where the

straight line segments intersect. Submit these coordinates as input data for the magnetization curve. The maximum density point must be submitted first.

Refer to Figure below for complete sample



- (19) k WATTS/LB - Core loss per lb of stator lamination material.
Must be given at the density specified in (20).
- (20) B DENSITY - This value must correspond to the density used in Item (19) to pick the watts/lb. The density that is usually used is 77.4 kilolines/in².

- (21) 1 TYPE OF STATOR SLOT - Refer to Figure 1
 2 for type of slot.
 3 For (a) slot use 1. as an input
 4 For (b) slot use 2. as an input
 5 For (c) slot use 3. as an input
 For (d) slot use 4. as an input
 Type 5. is not a slot but instead a particular situation for an open slot where the winding has only one conductor per slot.
- (22) b₀} ALL SLOT DIMENSIONS - Given in inches per Figure 1,
 b₁
 b₂
 b₃
 b_s Where the dimension does not apply
 h₀
 h₁
 h₂
 h₃
 h_s
 h_t
 h_w
 b_s = $\frac{(b_1) + (b_2)}{2} = \frac{(z_2) + (z_2)}{2}$
- (23) Q STATOR SLOTS - Number of.
- (24) h_c DEPTH BELOW SLOTS - The depth of the stator core below the slots.

Due to mechanical strength reasons, h_c should never be less than 70% of h_s .

$$h_c = \frac{(D) - [(d) + 2(h_s)]}{2} = \frac{(12) - [(11) + 2(22)]}{2}$$

(25) q SLOTS PER POLE PER PHASE

$$q = \frac{(Q)}{(P)(m)} = \frac{(23)}{(6)(5)}$$

(26) T_s STATOR SLOT PITCH

$$T_s = \frac{\pi(d)}{Q} = \frac{\pi(11)}{(23)}$$

(27) $T_{s1/3}$ STATOR SLOT PITCH - 1/3 distance up from narrowest section. For slot (a), (b), (c), and (e)

$$T_{s1/3} = \frac{\pi[(d) + .66(h_s)]}{(Q)} = \frac{\pi[(11) + .66(22)]}{(23)}$$

For slot (d)

$$\frac{\pi[(d) + 2(h_0) + 1.32(b_s)]}{(Q)} =$$

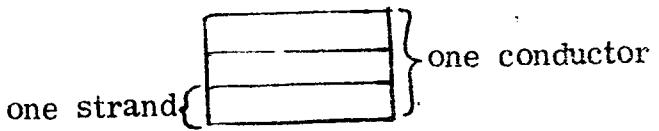
$$\frac{\pi[(11) + 2(22) + 1.32(22)]}{(23)}$$

(28) -- TYPE OF WINDING - Record whether the connection is "wye" or "delta". For "wye" conn use 1. for input. For "delta" use 0. for input.

(29) -- TYPE OF COIL - Record whether random wound or formed coils are used. For random wound coils use 0. for input. For formed coils use 1. for input.

(30)	n_s	<u>CONDUCTORS PER SLOT</u> - The actual number of conductors per slot. For random wound coils use a space factor of 75% to 80%. Where space factor is the percent of the total slot area that is available for insulated conductors after all other insulation areas have been subtracted out.
(31)	γ	<u>THROW</u> - Number of slots spanned. For example, with a coil side in slot 1 and the other coil side in slot 10, the throw is 9.
(31a)		<u>PER UNIT OF POLE PITCH SPANNED</u> - Ratio of the number of slots spanned to the number of slots in a pole pitch. This value must be between 1.0 and 0.5 to satisfy the limits of this program.
		$= \frac{(\gamma)}{(m)(q)} = \frac{(31)}{(5)(25)}$
(32)	C	<u>PARALLEL PATHS, No. of</u> - Number of parallel circuits per phase.
(33)	--	<u>STRAND DIA. OR WIDTH</u> - In inches. For round wire, use strand diameter. For rectangular wire, use strand width. This must be the largest of the two dimensions given for a rectangular wire.
(34)	NST	<u>NUMBER OF STRANDS PER CONDUCTOR IN DEPTH</u> - Applies to rectangular wire. In order to have a more flexible conductor and reduce eddy current loss, a stranded conductor is often used. For

example, when the space available for one conductor is .250 width x .250 depth, the actual conductor can be made up of 2 or 3 strands in depth as shown



For a more detailed explanation refer to section titled "Effective Resistance and Eddy Factor" in the Derivations in Appendix.

(34a)	N' ST	<u>NUMBER OF STRANDS PER CONDUCTOR</u> - This number applies to the strands in depth and/or width and is used in calculating the conductor area. Item (34) is different in that it deals with strands in depth only and is used in calculating eddy factors.
(35)	d_b	<u>DIAMETER OF BENDER PIN</u> - in inches - This pin is used in forming coils. Use .25 inch for stator O.D. < 8 inches use .50 inches for stator O.D. ≥ 8 inches.
(36)	ℓ_{e2}	<u>COIL EXTENSION BEYOND CORE</u> in Inches - Straight portion of coil that extends beyond stator core.
(37)	h_{ST}	<u>HEIGHT OF UNINSULATED STRAND</u> in Inches - This value is the vertical height of the strand and is used in eddy factor calculations. Set this value = 0 for round wire.
(38)	h'_{ST}	<u>DISTANCE BETWEEN CENTERLINES OF STRANDS IN DEPTH</u> in inches.

(39)	--	<u>STATOR COIL STRAND THICKNESS</u> in inches - For rectangular conductors only. For round wire insert 0. on input sheet. This must be the narrowest dimension of the two dimensions given for a rectangular wire.
(40)	τ_{SK}	<u>SKEW</u> - Stator slot skew in inches at stator I.D.
(41)	τ_P	<u>POLE PITCH</u> in inches. $\tau_P = \frac{\pi(d)}{(P)} = \frac{\pi(11)}{(6)}$
(42)	K_{SK}	<u>SKEW FACTOR</u> - The skew factor is the ratio of the voltage induced in the coils to the voltage that would be induced if there were no skew. When $\tau_{SK} = 0$, $K_{SK} = 1$ $K_{SK} = \frac{\sin \left[\frac{\pi(\tau_{SK})}{2(\tau_P)} \right]}{\frac{\pi(\tau_{SK})}{2(\tau_P)}} = \frac{\sin \left[\frac{\pi(40)}{2(41)} \right]}{\frac{\pi(40)}{2(41)}}$
(42a)		<u>PHASE BELT ANGLE</u> - Input For phase belt angle = 60° insert 60 on input sheet. For phase belt angle = 120° insert 120 on input sheet.
(43)	K_d	<u>DISTRIBUTION FACTOR</u> - The distribution factor is the ratio of the voltage induced in the coils to the voltage that would be induced if the windings

were concentrated in a single slot. See Table 2 for compilation of distribution factors for the various harmonics.

For 60° phase belt angle and $q = \text{integer}$ when
 $(42a) = 60$ and $(25) = \text{integer}$.

$$K_d = \frac{\sin 30^\circ}{(q) \sin [30/(q)]} = \frac{\sin 30^\circ}{(25) \sin [30/(25)]}$$

For 60° phase belt angle and $(q) \neq \text{integer} = N/B$
reduced to lowest terms.

When $(43a) = 1$ and $(25) \neq \text{integer} = N/B$ reduced
to lowest terms

$$K_d = \frac{\sin 30^\circ}{(N) \sin [30/(N)]} = \frac{\sin 30^\circ}{(43) \sin [30/(43)]}$$

For 120° phase belt angle and $(q) = \text{integer}$

When $(43a) = 120$ and $(25) = \text{integer}$

$$K_d = \frac{\sin 60^\circ}{2(q) \sin [30/(q)]} = \frac{\sin 60^\circ}{2(25) \sin [30/(25)]}$$

For 120° phase belt angle and $q = \text{integer}$

When $(43a) = 120$ and $(25) \neq \text{integer} = N/B$ re-
duced to lowest terms

$$K_d = \frac{\sin 60^\circ}{2(N) \sin [30/(N)]} = \frac{\sin 60^\circ}{2(43) \sin [30/(43)]}$$

(44) K_p PITCH FACTOR - The ratio of the voltage induced in the coil to the voltage that would be induced in a full pitched coil. See Table 1 for compilation of the pitch factors for the various harmonics.

$$K_p = \sin \left[\frac{(Y)}{(m)(q)} \times 90^\circ \right] = \sin \left[\frac{(31)}{(5)(25)} \times 90^\circ \right]$$

(45) n_e TOTAL EFFECTIVE CONDUCTORS - The actual number of effective series conductors in the stator winding taking into account the pitch and skew factors but not allowing for the distribution factor.

$$n_e = \frac{(Q)(n_s)(K_p)(K_{SK})}{(C)} = \frac{(23)(30)(44)(42)}{(32)}$$

(46) a_c CONDUCTOR AREA OF STATOR WINDING in (inches)² - The actual area of the conductor taking into account the corner radius on square and rectangular wire. See the following table for typical values of corner radii

$$\text{If } (39) = 0 \text{ then } a_c = .25\pi(\text{Dia})^2 = .25\pi(33)^2$$

If $(39) \neq 0$ then $a_c = (N' ST) \left[(\text{strand width})(\text{strand depth}) - (.858 r_c^2) \right] = (34a) \left[(33)(39) - (.858 r_c^2) \right]$
where $.858 r_c^2$ is obtained from Table V below.

<u>(39)</u>	<u>(33) .188</u>	<u>.189 (33) .75</u>	<u>(33) .751</u>
.050	.000124	.000124	.000124
.072	.000210	.000124	.000124
.125	.000210	.00084	.000124
.165	.000840	.00084	.003350
.225	.001890	.00189	.003350
.438	--	.00335	.007540
.688	--	.00754	.01340
--	--	.03020	.03020

TABLE V

(47)

 S_S

CURRENT DENSITY - Amperes per square inch of stator conductor

$$S_S = \frac{(I_{PH})}{(C)(a_c)} = \frac{(8)}{(32)(46)}$$

(48)

 L_E

END EXTENSION LENGTH in inches - Can be an input or output.

For L_E to be output, insert 0. on input sheet.

For L_E to be input, calculate per following:

When (29) = 0. then:

$$L_E = .5 + \frac{K_T \pi(Y) [(d) + (h_s)]}{Q} = .5 + \frac{[1.3 \text{ If } (6) = 2]}{[1.5 \text{ If } (6) = 4]} \pi(31) [(11) + (22)] \quad (23)$$

When (29) = 1. then:

$$\begin{aligned} L_E &= 2 \ell_{e2} + \pi \left[\frac{h_1}{2} + \text{dia} \right] + Y \left[\frac{T_s^2}{\sqrt{T_s^2 - b_s^2}} \right] \\ &= 2 (36) + \pi \left[\frac{(22)}{2} + (35) \right] + (31) \left[\frac{(26)^2}{\sqrt{(26)^2 - (22)^2}} \right] \end{aligned}$$

(49)

 ℓ_t

1/2 MEAN TURN - The average length of one conductor in inches.

$$\ell_t = (\ell) + (L_E) = (13) + (44)$$

(50)

 $X_s^0 D$

STATOR TEMP $^{\circ}\text{C}$ - Input temp at which F.L. losses will be calculated. No load losses and cold resistance will be calculated at 20°C .

(51)

 ρ_s

RESISTIVITY OF STATOR WINDING - In micro ohm-inches @ 20° C. If tables are available using units other than that given above, use Table VI for conversion to ohm-inches.

ρ	ohm-cm	ohm-in	ohm-cir mil/ft
1 ohm-cm =	1.000	0.3937	6.015×10^6
1 ohm-in =	2.540	1.000	1.528×10^7
1 ohm-cir mil/ft =	1.662×10^{-7}	6.545×10^{-8}	1.000

TABLE VI
Conversion Factors for Electrical Resistivity

(52)

 ρ_s
(hot)

RESISTIVITY OF STATOR WINDING - Hot at X_s °C in micro ohm-inches

$$\rho_{s(\text{hot})} = (\rho_s) \left[\frac{(X_s \text{ } ^\circ\text{C}) + 234.5}{254.5} \right] = (51) \left[\frac{(50) + 234.5}{254.5} \right]$$

(53)

 R_{SPH}
(cold)

STATOR RESISTANCE/PHASE - Cold @ 20°C in ohms

$$R_{SPH(\text{cold})} = \frac{(\rho_s)(n_s)(Q)(l_t)}{(m)(a_c)(C)^2} \times 10^{-6} = \frac{(51)(30)(23)(49)}{(5)(46)(32)^2} \times 10^{-6}$$

(54)

 R_{SPH}
(hot)

STATOR RESISTANCE/PHASE - Calculated @ X °C in ohms

$$R_{SPH(\text{hot})} = \frac{(\rho_s \text{ hot})(n_s)(Q)(l_t)}{(m)(a_c)(C)^2} \times 10^{-6} \frac{(52)(30)(23)(49)}{(5)(46)(32)^2} \times 10^{-6}$$

(55)

EF
(top)

EDDY FACTOR TOP - The eddy factor of the top coil. Calculate this value at the expected operating temperature of the machine. For round wire

$$EF_{\text{top}} = 1$$

(56) EF
(bot)

EDDY FACTOR BOTTOM - The eddy factor of the bottom coil at the expected operating temperature of the machine. For round wire $EF_{(bot)} = 1$

$$EF_{(bot)} = (EF_{(top)}) - 1.677 \left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_{shot})} \right]^2 \times 10^{-3}$$

$$= (55) - 1.677 \left[\frac{(37)(30)(5a)(46)}{(22)(52)} \right] 10^{-3}$$

(57) b_{tm}

STATOR TOOTH WIDTH 1/2 way down tooth in inches -
For slots type (a), (b), (d) and (e), Figure I

$$b_{tm} = \frac{\pi \sqrt{d + (h_s)}}{(Q)} - (b_s) = \frac{\pi \sqrt{11 + (22)}}{(23)} - (22)$$

(57a)

 $b_t \frac{1}{3}$ STATOR TOOTH WIDTH 1/3 distance up from narrowest section

For slots type (a), (b) and (e)

$$b_t \frac{1}{3} = (\tau_s \frac{1}{3}) - (b_s) = (27) - (22)$$

For slot type (c)

$$b_t \frac{1}{3} = b_{tm} = (57)$$

For slot type (d)

$$b_t \frac{1}{3} = (\tau_1 \frac{1}{3}) - \frac{2\sqrt{2}}{3} (b_s) = (27) - .94(22)$$

(58)

 b_t TOOTH WIDTH AT STATOR I.D. in inches -

For partially closed slot

$$b_t = \frac{\pi(d)}{(Q)} - b_0 = \frac{\pi(11)}{(23)} - (22)$$

For open slot

$$b_t = \frac{\pi(d)}{(Q)} - b_s = \frac{\pi(11)}{(23)} - (22)$$

(59)	g_{\min}	<u>MINIMUM AIR GAP</u> in inches - For concentric pole face $g_{\min} = g_{\max}$. For non concentric pole face g_{\min} = gap at the center of the pole.
(59a)	g_{\max}	<u>MAXIMUM AIR GAP</u> in inches
(60)	C_X	<u>REDUCTION FACTOR</u> - Used in calculating conductor permeance and is dependent on the pitch and distribution factor. This factor can be obtained from Graph 1 with an assumed K_d of .955 or calculated as shown
		$C_X = \frac{(K_X)}{(K_P)^2 (K_d)^2} = \frac{(61)}{(44)^2 (43)^2}$
		NOTE: See special case for (e) slot referred to calculation (62)
(61)	K_X	<u>FACTOR TO ACCOUNT FOR DIFFERENCE</u> in phase current in coil sides in same slot $K_X = \frac{1}{4} \left[\frac{3(Y)}{(m)(q)} + 1 \right] \text{ For 3 phase}$ $= \frac{1}{4} \left[\frac{3(31)}{(5)(25)} + 1 \right]$ $K_X = \frac{(Y)}{(m)(q)} \text{ For 2 phase}$ $= \frac{(31)}{(5)(25)}$
		NOTE: See special case for (e) slot. Refer to calculation (62)
(62)	λ_i	<u>CONDUCTOR PERMEANCE</u> - The specific permeance for the portion of the stator current that is embedded in the iron. This permeance depends upon the configuration of the slot.

(a) For open slots

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)} \right]$$

(b) For partially closed slots with constant slot width

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_o)}{(b_o)} + \frac{2(h_t)}{(b_o) + (b_s)} + \frac{(h_w)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{2(22)}{(22) + (22)} + \frac{(22)}{(22)} + \frac{(22)}{3(22)} + \frac{(58)^2}{16(26)(59)} + \frac{.35(58)}{(26)} \right]$$

(d) For round slots

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[.62 + \frac{(h_o)}{(b_o)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[.62 + \frac{(22)}{(22)} \right]$$

(e) For open slots with a winding of one conductor per slot

$$\lambda_i = (C_X) \frac{20}{(m)(q)} \left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + .6 + \frac{(g)}{2(\tau_s)} + \frac{(\tau_s)}{4(g)} \right]$$

$$\lambda_i = (60) \frac{20}{(5)(25)} \left[\frac{(22)}{(22)} + \frac{(22)}{3(22)} + .6 + \frac{(59)}{2(26)} + \frac{(26)}{4(59)} \right]$$

$$\left(C_X = \frac{1}{(K_p^2)(K_d^2)} \right)$$

$$(K_X) = 1$$

(63)

 K_E LEAKAGE REACTIVE FACTOR for end turn

$$K_E = \frac{\text{Calculated value } (L_E)}{\text{Value } (L_E) \text{ from Graph 1}} \quad (\text{For machines where } (11) > 8")$$

where $L_E = (48)$ and abscisa of Graph 1 = $(Y)(T_s') = (31)(26)$

$$K_E = \sqrt{\frac{\text{Calculated value of } (L_E)}{\text{Value } (L_E) \text{ from Graph 1}}} \quad (\text{For machines where } (11) < 8")$$

(64)

 λ_E END WINDING PERMEANCE - The specific permeance for the end extension portion of the stator winding

$$\lambda_E = \frac{6.28(K_E)}{(\ell)(K_d)^2} \left[\frac{\phi_E L_E}{2n} \right] = \frac{6.28(63)}{(13)(43)^2} \left[\frac{Q_E L_E}{2n} \right]$$

The term $\left[\frac{\phi_E L_E}{2n} \right]$ is obtained from Graph 1.

The symbols used in this (term) do not apply to those of this design manual. Reference information for the symbol origin is included on Graph 1.

(65)

--

WEIGHT OF COPPER - The weight of stator copper in lbs.

$$\# \text{ s copper} = .321(n_s)(Q)(a_c)(t) = .321(30)(23)(46)(49)$$

(66)

--

WEIGHT OF STATOR IRON - in lbs.

$$\# \text{ s iron} = .283 \left\{ (b_{tm})(Q)(\ell_s)(h_s) + \pi [D - (h_c)] (h_c) (\ell_s) \right\}$$

$$.283 \left\{ (57)(23)(17)(22) + \pi [(12) - (24)] (24)(17) \right\}$$

(67)

 K_s CARTER COEFFICIENT

$$K_s = \frac{(T_s) \left[5(g) + (b_s) \right]}{(T_s) \left[5(g) + (b_s) \right] - (b_s)^2} \quad (\text{For open slots})$$

$$K_s = \frac{(26) [5(59) + (22)]}{(26) [5(59) + (22)] - (22)^2}$$

$$K_s = \frac{\tau_s [4.44(g) + .75(b_o)]}{\tau_s [4.44(g) + .75(b_o)] - (b_o)^2} \text{ (For partially closed slots)}$$

$$K_s = \frac{(26) [4.44(59) + .75(22)]}{(26) [4.44(59) + .75(22)] - (22)^2}$$

(68) -- AIR GAP AREA - The area of the gap surface at the stator bore

$$\text{Gap Area} = \pi(d)(l) = \pi(11)(13)$$

(69) g_e EFFECTIVE AIR GAP

$$g_e = (K_s)(g) = (67)(59)$$

(70) λ_a AIR GAP PERMEANCE - The specific permeance of the air gap

$$\lambda_a = \frac{6.38(d)}{(P)(g_e)} = \frac{6.38(11)}{(6)(69)}$$

(71) C_1 THE RATIO OF MAXIMUM FUNDAMENTAL of the field form
to the actual maximum of the field form - This term
can be an input or output. For C_1 to be output insert
0. on input sheet. For C_1 to be input, determine C_1
as follows:

For pole heads with only one radius, C_1 is obtained
from curve #4. The abscissa is "pole embrace" (α)
= (77). The graphical flux plotting method of deter-
mining C_1 is explained in the section titled "Deriva-
tions" in the Appendix.

(72) C_W

WINDING CONSTANT - The ratio of the RMS line voltage for a full pitched winding to that which would be introduced in all the conductors in series if the density were uniform and equal to the maximum value. This value can be an input or output. For C_W to be an output, insert 0. on input sheet. For C_W to be an input, calculate as follows:

$$C_W = \frac{(E)(C_1)(K_d)}{\sqrt{2} (E_{PH})(m)} = \frac{(3)(71)(43)}{\sqrt{2} (4)(5)}$$

Assuming $K_d = .955$, then $C_W = .225 C_1$ for three phase delta machines and $C_W = .390 C_1$ for three phase star machines.

(73) C_P

POLE CONSTANT - The ratio of the average to the maximum value of the field form. This ratio can be an input or output. For C_P to be an output, insert 0. on input sheet. For C_P to be an input, determine as follows:

For pole heads with more than one radius C_P is calculated from the same field form that was used to determine C_1 , and this method is described in the section titled "Derivations" in the Appendix. For pole heads with only one radius C_P is obtained from curve #4. Note the correction factor at the top of the curve.

(74) C_M

DEMAGNETIZING FACTOR - direct axis - This factor can be an input or output. For C_M to be an output, insert 0. on input sheet. For C_M to be an input, determine as follows:

$$C_M = \frac{(\alpha)\pi + \sin[(\alpha)\pi]}{4 \sin[(\alpha)\pi/2]} = \frac{(77)\pi + \sin[(77)\pi]}{4 \sin[(77)\pi/2]}$$

C_M can also be obtained from curve 9.

(75) C_q

CROSS MAGNETIZING FACTOR - quadrature axis - This factor can be an input or output. For C_q to be an output, insert 0. on input sheet. For C_q to be an input, determine as follows:

$$C_q = \frac{1/2 \cos[(\alpha)\pi/2] + (\alpha)\pi - \sin[(\alpha)\pi]}{4 \sin[(\alpha)\pi/2]}$$

$$= \frac{1/2 \cos[(77)\pi/2] + (77)\pi - \sin[(77)\pi]}{4 \sin[(77)\pi/2]}$$

} VALID FOR CONCENTRIC POLES.

C_q can also be obtained from curve 9.

(76) --

POLE DIMENSIONS LOCATIONS per Figure 2

Where:

b_h = width of pole head

b_p = width of pole body

h_h = height of pole head at center

h_p = height of pole body (Magnet)

l_p = length of pole body

l_h = length of pole head

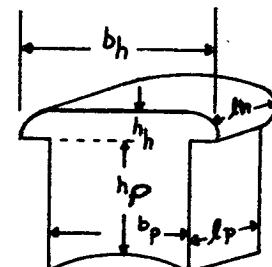


Fig. 2

all dimensions in inches

(77) α

POLE EMBRACE

$$\alpha = \frac{b_h}{T_p} = \frac{(76)}{(41)}$$

(78)

A

AMPERE CONDUCTORS per inch - The effective ampere conductors per inch of stator periphery. This factor indicates the "specific loading" of the machine. Its value will increase with the rating and size of the machine and also will increase with the number of poles. It will decrease with increases in voltage or frequency. A is generally higher in single phase machines than in polyphase ones.

$$A = \frac{(I_{PH})(n_s)(K_p)}{(C)(\tau_s)} = \frac{(8)(30)(44)}{(32)(26)}$$

(79)

X

REACTANCE FACTOR - The reactance factor is the quantity by which the specific permeance must be multiplied to give percent reactance. It is the percent reactance for unit specific permeance, or the percent of normal voltage induced by a fundamental flux per pole per inch numerically equal to the fundamental armature ampere turns at rated current. Specific permeance is defined as the average flux per pole per inch of core length produced by unit ampere turns per pole.

$$X = \frac{100(A)(K_d)}{\sqrt{2} (C_1)(B_g) \times 10^3} = \frac{100(78)(43)}{\sqrt{2} (71)(125) \times 10^3}$$

(80)

 X_L

LEAKAGE REACTANCE - The leakage reactance of the stator for steady state conditions. When (5) = 3, calculate as follows:

$$X_L = X [(\lambda_i) + (\lambda_E)] = (79)[(62) + (64)]$$

In the case of two phase machines a component due to belt leakage must be included in the stator leakage reactance. This component is due to the harmonics

caused by the concentration of the MMF into a small number of phase belts per pole and is negligible for three phase machines. When $(5) = 2$, calculate as follows:

$$\lambda_B = \frac{0.1(d)}{(P)(g_e)} \left[\frac{\sin \left[\frac{3(y)}{(m)(q)} \right] 90^\circ}{(K_p)} \right] = \frac{0.1(11)}{(6)(69)} \left[\frac{\sin \left[\frac{3(31)}{(5)(25)} \right] 90^\circ}{(44)} \right]$$

$$X_L = X[(\lambda_i) + (\lambda_E) + (\lambda_B)] \text{ where } \lambda_B = 0 \text{ for 3 phase machines.}$$

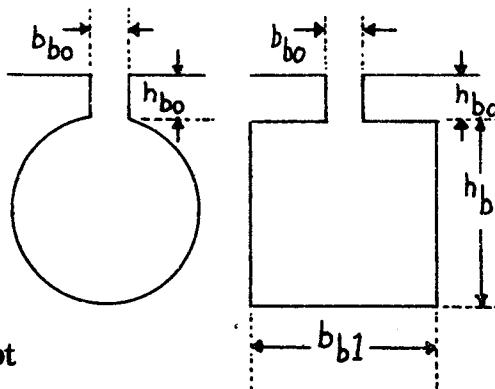
$$X_L = (79)[(62) +)64) + (80)]$$

(85) a_p POLE AREA - The net cross-sectional area of the pole.

$$a_p = (b_p)(l_p) = (76)(76)(16)$$

(89)

--

DAMPER SLOT DIMENSIONS b_{bo} - width of slot opening h_{bo} - height of slot opening h_b - diameter of round slot h_{b1} - height of bar section of slot b_{b1} - width of rectangular slot

(90)

--

DAMPER BAR DIA OR WIDTH in inches

(91)

 h_{b1}

DAMPER BAR THICKNESS in inches - Damper bar thickness considered equal to damper bar slot height (h_b) per Item (89). Set this item = 0 for round bar.

(92)

 n_b NUMBER OF DAMPER BARS PER POLE

(93)

 ℓ_b DAMPER BAR LENGTH in inches

(94)

 T_b DAMPER BAR PITCH in inches

(95)

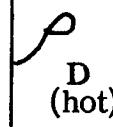
 ρ_D

RESISTIVITY of damper bar @ 20°C in ohm-inches - Refer to table given in Item (51) for conversion factors.

(96)

 X_D °C

DAMPER BAR TEMP °C - Input temp at which damper losses are to be calculated.

(97) 

RESISTIVITY OF DAMPER BAR @ X_D °C

$$\rho_{D \text{ (hot)}} = \rho_D \frac{(X_D \text{ } ^\circ\text{C})}{254.5} \frac{234.5}{254.5} = (95) \frac{(96)}{254.5} \frac{234.5}{254.5}$$

(98) a_{cd}

CONDUCTOR AREA OF DAMPER BAR - Calculate same
as stator conductor area

At (46) except substitute $\begin{cases} (91) \text{ for (39)} \\ (90) \text{ for (33)} \end{cases}$

If (91) = 0

$$a_{cd} = .25 \pi (\text{damper bar dia})^2 = .25 \pi (90)^2$$

If (91) ≠ 0

$$a_{cd} = (h_{b1}) (\text{damper bar width}) = (91)(90)$$

(109) λ_b

PERMEANCE OF DAMPER BAR - The permeance of that portion of the damper bar that is embedded in pole iron.

For round slot

$$\lambda_b = 6.38 \left[\frac{(h_{bo})}{(b_{bo})} + .62 + .5 \right] = 6.38 \left[\frac{(89)}{(89)} + .62 + .5 \right]$$

For rectangular slot

$$\lambda_b = 6.38 \left[\frac{(h_{bo})}{(b_{bo})} + \frac{(h_{b1})}{3(b_{b1})} + .5 \right] = 6.38 \left[\frac{(89)}{(89)} + \frac{(89)}{3(89)} + .5 \right]$$

(110)

 λ_{pt} PERMEANCE OF END PORTION OF DAMPER BARS

$$\lambda_{pt} = 6.38 \left\{ \frac{(b_h) - (\tau_b) [(n_b) - 1]}{3(g_e)} \right\}$$

$$= 6.38 \left\{ \frac{(76) - (94) [(92) - 1]}{3(69)} \right\}$$

(114)

 λ_{Dd} PERMEANCE OF DAMPER BAR - in direct axis

$$\begin{aligned} \lambda_{Dd} &= \left\{ \cos \left[\frac{\{(n_b) - 1\} (\tau_b) \pi}{2(\tau_p)} \right] \right\} \left\{ \frac{\{(\lambda_b) + (\lambda_{Pt})\} (\lambda_F)}{\lambda_b + \lambda_{Pt} + \lambda_F} \right\} \\ &= \left\{ \cos \left[\frac{\{(92) - 1\} (94)}{2(94)} \right] \right\} \left\{ \frac{\{(109) + (110)\} (111)}{(109) + (110) (111)} \right\} \end{aligned}$$

(115)

 X_{Dd} DAMPER LEAKAGE REACTANCE - in direct axis

$$X_{Dd} = X(\lambda_{Dd}) = (79)(114)$$

(116)

 λ_{Dq} PERMEANCE IN QUADRATURE AXIS

For round slot

$$\lambda_{Dq} = \frac{20(\tau_b)}{(\tau_p)} \left[\frac{(h_{bo})}{(b_{bo})} + .62 + .5 + \frac{(g)}{(\tau_b)} \right]$$

$$= \frac{20(94)}{(41)} \left[\frac{(89)}{(89)} + .62 + .5 + \frac{(59)}{(94)} \right]$$

For rectangular slot

$$\lambda_{(Dq)} = \frac{20(\tau_b)}{(\tau_p)} \left[\frac{(h_{bo})}{(b_{bo})} + \frac{(h_{b1})}{3(b_{b1})} + .5 + \frac{(g)}{(\tau_b)} \right]$$

$$= \frac{20(94)}{(41)} \left[\frac{(89)}{(89)} + \frac{(89)}{3(89)} + .5 + \frac{(59)}{(94)} \right]$$

(117)

 X_{Dq} DAMPER LEAKAGE REACTANCE - in quadrature axis

$$X_{Dq} = X(\lambda_{Dq}) = (79)(116)$$

(120)	X''_d	<u>SUBTRANSIENT REACTANCE</u> in direct axis When damper bars exist, i.e. when (92) $\neq 0$ $X''_d = (X'_d) + (X_{Dd}) = (80) + (115)$ When no damper bars exist, i.e. when (92) = 0 $X''_d = (X'_d) = (X_d)$
(124)	ϕ_T	<u>TOTAL FLUX IN KILOLINES</u> $\phi_T = \frac{6(E)10^6}{(C_W)(n_e)(RPM)} = \frac{6(3)10^6}{(72)(45)(17)}$
(125)	B_g	<u>GAP DENSITY</u> in Kilolines/in ² - The maximum flux density in the air gap $B_g = \frac{(\phi_T)}{\pi(d)(l)} = \frac{(124)}{\pi(11)(13)}$
(126)	ϕ_P	<u>FLUX PER POLE</u> in Kilolines $\phi_P = \frac{(\phi_T)(C_P)}{(P)} = \frac{(124)(73)}{(6)}$
(127)	B_t	<u>TOOTH DENSITY</u> in Kilolines/in ² - The flux density in the stator tooth at 1/3 of the distance from the minimum section. $B_t = \frac{\phi_T}{(Q)(l_s)(b_t 1/3)} = \frac{(124)}{(23)(17)(57a)}$

(128)	B_c	<u>CORE DENSITY</u> in Kilolines/in ² - The flux density in the stator core
		$B_c = \frac{(\phi_p)}{2(h_c)(l_s)} = \frac{(126)}{2(24)(17)}$
(129)	F_T	<u>STATOR TOOTH AMPERE TURNS</u>
		$F_T = h_s \left[NI/in \text{ at density } B_t \right]$ $= (22) \left[\text{Look up on stator magnetization curve given in (18) @ density (127)} \right]$
(130)	F_c	<u>STATOR CORE AMPERE TURNS</u>
		$F_c = \left[\frac{\pi[(D) - (h_c)]}{4(P)} \right] \left[NI/in @ \text{density of } B_c \right]$ $= \left[\frac{\pi[(12) - (24)]}{4(6)} \right] \left[\text{Look-up on stator magnetization curve given in (18) @ density (128)} \right]$
(130a)	F_s	<u>STATOR AMPERE TURNS, total</u>
		$F_s = (F_T) + (F_c) = (129) + (130)$
(131)	F_g	<u>AIR GAP AMPERE TURNS</u> - The field ampere turns per pole required to force flux across the air gap when operating at no load with rated voltage.
		$F_g = \frac{(B_g)(g_e)}{3.19} = \frac{(125)(69)}{3.19}$

(147) F&W FRICITION & WINDAGE LOSS - There is no known calculation method that will give accurate results for this loss. The best results are obtained by using existing data. For ratioing purposes, the loss can be assumed to vary approximately as the 5/2 power of the rotor diameter and as the 3/2 power of the RPM. When no existing data is available, the following calculation can be used for an approximate answer. Insert 0. when computer is to calculate F&W. Insert actual F&W when available. Use same value for all load conditions.

$$F \& W = 2.52 \times 10^{-6} (d_r)^{2.5} (\ell_h) (\text{RPM})^{1.5}$$

$$= 2.52 \times 10^{-6} (11a)^{2.5} (76) (7)^{1.5}$$

(148) W_{TNL} STATOR TEETH LOSS - at no load. The no load loss (W_{TNL}) consists of eddy current and hysteresis losses in the iron. For a given frequency the no load tooth loss will vary as the square of the flux density.

$$W_{TNL} = .453(b_t 1/3)(Q)(\ell_s)(h_s)(K_Q)$$

$$= .453(57a)(23)(17)(22)(148)$$

$$\text{Where } K_Q = (k) \left[\frac{(B_t)}{(B)} \right]^2 = (19) \left[\frac{(127)}{(20)} \right]^2$$

(149) W_c

STATOR CORE LOSS - The stator core losses are due to eddy currents and hysteresis and do not change under load conditions. For a given frequency the core loss will vary as the square of the flux density (B_c).

$$W_c = 1.42 \left[(D) - (h_c) \right] (h_c)(\ell_s)(K_Q)$$

$$= 1.42 \left[(12) - (24) \right] (24)(17)(149)$$

$$\text{Where } K_Q = (k) \left[\frac{(B_c)}{(B)} \right]^2 = (19) \left[\frac{(128)}{(20)} \right]^2$$

(150) W_{NPL}

POLE FACE LOSS - at no load. The pole surface losses are due to slot ripple caused by the stator slots. They depend upon the width of the stator slot opening, the air gap, and the stator slot ripple frequency. The no load pole face loss (W_{PNL}) can be obtained from Graph 2. Graph 2 is plotted on the bases of open slots. In order to apply this curve to partially open slots, substitute b_o for b_s . For a better understanding of Graph 2, use the following sample.

K_1 as given on Graph 2 is derived empirically and depends on lamination material and thickness. Those values given on Graph 2 have been used with success. K_1 is an input and must be specified. See item (151) for values of K_1 .

(150) (Cont.)

K_2 is shown as being plotted as a function of $(B_G)^{2.5}$. Also note that upper scale is to be used. Another note in the lower right hand corner of graph indicates that for a solid line (—), the factor is read from the left scale, and for a broken or dashed line (— - — -), the right scale should be read. For example, find K_2 when $B_G = 30$ kilo lines. First locate 30 on upper scale. Read down to the intersection of solid line plot of $K_2 = f(B_G)^{2.5}$. At this intersection read the left scale for K_2 . $K_2 = .28$. Also refer to item (152) for K_2 calculations.

K_3 is shown as a solid line plot as a function of $(F_{SLT})^{1.65}$. The note on this plot indicates that the upper scale $\times 10$ should be used. Note F_{SLT} = slot frequency. For an example, find K_3 when $F_{SLT} = 1000$. Use upper scale $\times 10$ to locate 1000. Read down to intersection of solid line plot of $K_3 = f(F_{SLT})^{1.65}$. At this intersection read the left scale for K_3 . $K_3 = 1.35$. Also refer to item (153) for K_3 calculations.

For K_4 use same procedure as outlined above except use lower scale. Do not confuse the dashed line in this plot with the note to use the right scale. The note does not apply in this case. Read left scale. Also refer to item (154) for K_4 calculations.

For K_5 use bottom scale and substitute b_o for b_s when using partially closed slot. Read left scale when using solid plot. Use right scale when using dashed plot. Also refer to item (155) for K_5 calculations.

(150)	(Cont.)	<p>For K_6 use the scale attached for C_1 and read K_6 from left scale. Also refer to item (156) for K_6 calculations.</p> <p>The above factors (K_2), (K_3), (K_4), (K_5), (K_6) can also be calculated as shown in (152), (153), (154), (155), (156), respectively.</p> $W_{PNL} = \pi(d)(\ell)(K_1)(K_2)(K_3)(K_4)(K_5)(K_6)$ $= \pi(11)(13)(151)(152)(153)(154)(155)(156)$
(151)	K_1	<p>K_1 is derived empirically and depends on lamination material and thickness. The values used successfully for K_1 are shown on Graph 2. They are</p> <p>K_1 = 1.17 for .028 lam thickness, low carbon steel = 1.75 for .063 lam thickness, low carbon steel = 3.5 for .125 lam thickness, low carbon steel = 7.0 for solid core</p> <p>K_1 is an input and must be specified on input sheet.</p>
(152)	K_2	<p>K_2 can be obtained from Graph 2 (see item 150) for explanation of Graph 2) or it can be calculated as follows:</p> $K_2 = f(B_G) = 6.1 \times 10^{-5} (B_G)^{2.5}$ $= 6.1 \times 10^{-5} (125)^{2.5}$
(153)	K_3	<p>K_3 can be obtained from Graph 2 (see item 150) for explanation of Graph 2) or it can be calculated as follows:</p> $K_3 = f(F_{SLT}) = 1.5147 \times 10^{-5} (F_{SLT})^{1.65}$ $= 1.5147 \times 10^{-5} (153)^{1.65}$ <p>Where $F_{SLT} = \frac{(RPM)}{60} (Q)$</p> $= \frac{(7)}{60} (23)$

(154) K_4 can be obtained from Graph 2 (see item (150) for explanation of Graph 2) or it can be calculated as follows:

For $\tau_s \leq .9$

$$K_4 = f(\tau_s) = .81(\tau_s)^{1.285}$$

$$= .81(26)^{1.285}$$

For $.9 \leq \tau_s \leq 2.0$

$$K_4 = f(\tau_s) = .79(\tau_s)^{1.145}$$

$$= .79(26)^{1.145}$$

For $\tau_s > 2.0$

$$K_4 = f(\tau_s) = .92(\tau_s)^{.79}$$

$$= .92(26)^{.79}$$

(155) K_5 can be obtained from Graph 2 (see item (150) for explanation of Graph 2) or it can be calculated as follows:

For $(b_s)/(g) \leq 1.7$

$$K_5 = f(b_s/g) = .3[(b_s)/(g)]^{2.31}$$

$$= .3[(22)/(59)]^{2.31}$$

NOTE: For partially open slots substitute b_o for b_s in equations shown.

For $1.7 < (b_s)/(g) \leq 3$

$$K_5 = f(b_s/g) = .35[(b_s)/(g)]^2$$

$$= .35[(22)/(59)]^2$$

For $3 < (b_s) / (g) \leq 5$

$$K_5 = f(b_s) / (g) = .625 [(b_s) / (g)]^{1.4}$$

$$= .625 [(22) / (59)]^{1.4}$$

For $(b_s) / (g) > 5$

$$K_5 = f[(b_s)] / (g) = 1.38 [(b_s) / (g)]^{.965}$$

$$= 1.38 [(22) / (59)]^{.965}$$

- (156) K_6 can be obtained from Graph 2 (see item (150) for explanation of Graph 2) or it can be calculated as follows:

$$K_6 = f(C_1) = 10 [.9323(C_1) - 1.60596]$$

$$= 10 [.9323(71) - 1.60596]$$

- (157) w_{DNL} DAMPER LOSS - at no load at 20°C . This loss is produced by slot ripple in the damper winding. At no load this loss is calculated from curves 7 and 8.

$$w_{DNL} = \frac{1.246(P)(n_b)(l_b)(\rho_D)}{(a_{cr}) \times 10^3} \left[(\tau_s)(B_g)(K_{P1})(K_g) \right]^2$$

$$\left\{ (K_{f1}) \left[\frac{K_{W1}}{2(\lambda_s) + [(\lambda_g)/(K_{\phi 1})]} \right]^2 + (K_{f2}) \left[\frac{K_{W2}}{2(\lambda_s) + [(\lambda_g)/(K_{\phi 2})]} \right]^2 \right\}$$

$$w_{DNL} = \frac{1.246(6)(92)(93)(95)}{(98) \times 10^3} \left[(26)(125)(157)(157) \right]^2$$

$$\left\{ (157) \left[\frac{(157)}{2(157) + [(157)/(157)]} \right]^2 + (157) \left[\frac{(157)}{2(157) + [(157)/(157)]} \right]^2 \right\}$$

(157) (Cont.)

$$\text{Where } K_{P1} = 1 - \frac{1}{\sqrt{1 + [(b_s)/2(g)]^2}}$$

$$= 1 - \frac{1}{\sqrt{1 + [(22)/2(59)]^2}}$$

NOTE: Substitute b_o for b_s when partially opened stator slot is used.

K_{P1} can also be obtained from curve 7 where abscissa is $(b_s)/(g)$ or $(b_o)/(g) = (22)/(59)$

$$\text{Where } K_g = (K_s) = (67)$$

$$\text{Where } g' = (K_g)(g) = (157)(59)$$

Where K_{f1} & K_{f2} are obtained from curve 7

Where the abscissa is S_1 or S_2

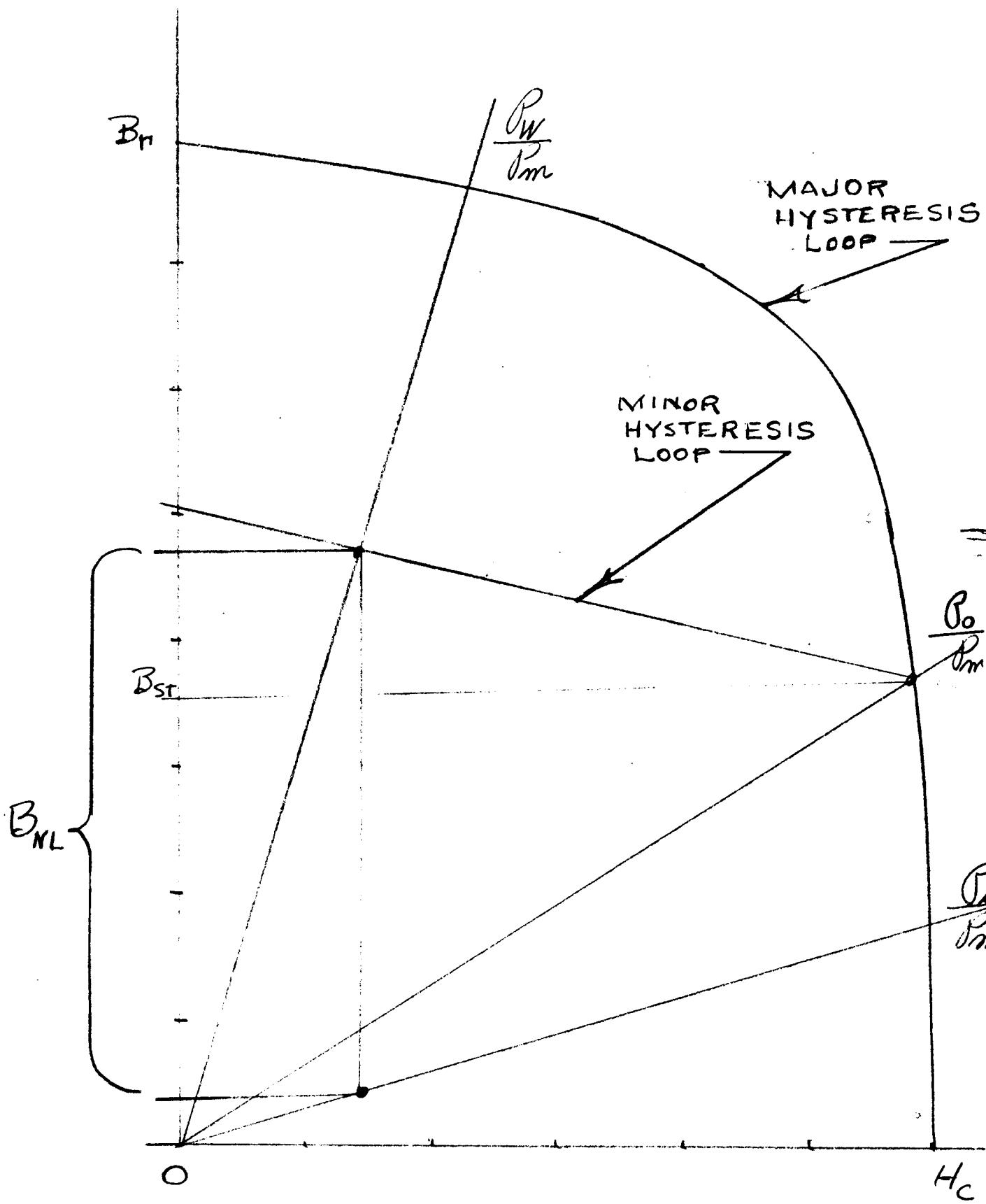
$$S_1 = 3.2 \sqrt{\frac{(f_{S1})}{D}} = 3.2 \sqrt{\frac{(157)}{(95)}}$$

$$S_2 = 3.2 \sqrt{\frac{(f_{S2})}{D}} = 3.2 \sqrt{\frac{(157)}{(95)}}$$

$$\text{Where } f_{S1} = 2qmf = 2(25)(5)(5a)$$

$$f_{S2} = 2(f_{S1})$$

Where K_{W1} and K_{W2} are obtained from curve 8.
where the abscissa is $(b_s)/(\tau_s)$ for open slots or
 $(b_o)/(\tau_s)$ for semi-enclosed slots $(b_s)/(\tau_s) = (22)/(26)$



(159)

--

TOTAL LOSSES - at no load. Sum of all losses

Total losses = (F&W) (Stator Teeth Loss)

(Stator Core Loss) (Pole Face Loss)

(Damper Loss)

= (146) (147) (148) (149) (150) (157)

NOTE: The output sheet shows the next items to be:

(Rating), (Rating Losses), (% Losses), (%

Efficiency). These items do not apply to the
no load calculation since the rating is zero.

Refer to Items (175), (176), (177), (178) for
these calculations under load.

Items (138) through (159) have been calculated for 0%
load or no load. They should all be repeated now for
100% load.

(157)	(Cont.)	<p>Where λ_t is obtained from curve 8</p> <p>Where the abscissa is $(b_{bo})/(g') = \frac{(89)}{(157)}$</p> <p>When $91 = 0$ or when $(90) = (91)$</p> $\lambda_C = \frac{.75}{(K_{f1})} = \frac{.75}{(157)} \text{ For round or square slots}$ <p>When $91 \neq 0$ and when $(90) \neq (91)$</p> $\lambda_C = \frac{(h_{b1})}{3(b_{b1})(K_{f1})} = \frac{(91)}{3(89)(157)}$ <p>Where $\lambda_S = \frac{(h_{bo})}{(b_{bo})} + (\lambda_t) + (\lambda_C)$</p> $= \frac{(89)}{(89)} + (157) + (157)$ <p>Where $\lambda_g = \frac{\tau_b}{g} = \frac{(94)}{(157)}$</p> <p>Where $K_{\phi 1}$ and $K_{\phi 2}$ are obtained from curve 8</p> <p>Where the abscissa is $(\tau_b)/(\tau_s) = (94)/(26)$</p>
(158)	$I^2 R$	<u>STATOR $I^2 R$</u> - at no load. This item = 0. Refer to item (173) for 100% load stator $I^2 R$.
(158a)	--	<u>EDDY LOSS</u> - at no load. This item = 0. Refer to item (173a) for 100% load eddy loss.

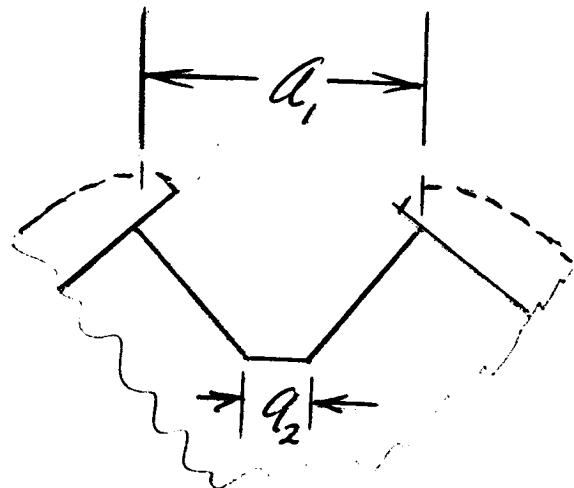
P_1 = Permeance of the flux leakage path from pole-side to pole-side.

$$P_1 = \ell_p P \left[1 - \frac{a_2}{a_1-a_2} \ln \left(1 + \frac{a_1-a_2}{a_2} \right) \right]$$

For the poles that do not touch at the base

$$P_1 = 3.19 \frac{P}{\pi} \ell_p \quad \text{or}$$

$$P_1 = P \ell_p \text{ for } a_2 = 0$$



P_2 = Permeance of the flux leakage paths from pole-head surface to pole-head surface and between adjacent pole head edges. This flux leakage is out-stator leakage that becomes useful flux when the rotor is installed in the stator.

$$P_2 = 1.66 (1 + 1.23 \ln \frac{1}{1-\alpha})$$

P_3 = Permeance of the flux leakage path between the ends of adjacent pole magnets.

$$P_3 = h_p (1.66) \left[1 + 1.23 \ln \left(1 + \frac{2}{\frac{a_1}{b_p} + \frac{a_2}{b_p}} \right) \right]$$

P_{s1} = Permeance of the flux leakage path between pole head edges and is for that portion of the leakage flux that still exists when the rotor is in the stator. It is between pole head undersides in some cases and pole edges in other cases. It is approximated as being edge to edge in the general case.

$$P_{s1} = \frac{6.38 h_h \ell_p}{\tau_r - b_p}$$

P_{s2} = Permeance of the flux leakage path between the end surfaces of the pole heads.

$$P_{s2} = \frac{2 h_h P_2}{\ell_p}$$

P_m = Adjustment factor to convert the permeance values to the proper scale for use in the general hysteresis loop.

$$P_m = \frac{\text{magnet area (net)}}{\text{magnet length}}$$

$$= \frac{\ell_p b_p}{2 h_p} C$$

Where C is a factor to account for holes or otherwise unaccountable discrepancies in magnet performance.

P_i = Permeance of the in-stator leakage flux.

$$P_i = P_{s1} + P_{s2} + P_1 + P_3$$

P_o = Permeance of the out-stator leakage flux.

$$P_o = P_i + P_2$$

P_g = Air-gap permeance.

$$= 3.19 \frac{\pi}{2} \frac{C_p d_r}{g_e P} l$$

$$= \frac{\lambda_a \pi}{4} C_p l$$

$$= .785 \lambda_a C_p l$$

$\frac{P_o}{P_m}$ = Slope of the out-stator permeance shear line

$\frac{P_i}{P_m}$ = Slope of the in-stator permeance shear line

P_w = Total apparent permeance of the working air gap. The total permeance of the magnet flux paths when the rotor is in the stator.

$$P_w = P_i + P_g$$

$\frac{P_w}{P_m}$ = Slope of the working-gap shear line.

A_T

The ampere-turn/inch of magnet value corresponding to the intersection of the shear line $\frac{P_o}{P_m}$ with the major hysteresis loop of the permanent magnet material.

This value A_T locates the lower end of the minor hysteresis loop and determines the maximum demagnetizing mmf that the magnet can endure without some loss of magnetic properties. Several curves of A_T versus out-stator shear line values $\frac{P_o}{P_m}$ are given in Curves 17, 18 and 19.

 E_{NL}

The no load voltage produced by the unregulated PM generator at rated speed.

$$E_{NL} = \frac{E (A_T)}{B_u} \frac{\left(\frac{P_o}{P_m} + h \right) \left(\frac{P_w}{P_m} - \frac{P_i}{P_m} \right)}{\left(\frac{P_w}{P_m} + h \right)}$$

B_u = magnet flux density calculated for E rated NL.

$$F_{dm} = \frac{.45 I N_e C_m K_d}{P}$$

I = Rated Amperes

$$H_{d1} = \frac{F_{dm}}{h_p}$$

$$A_x = \frac{A_T \left(\frac{P_o}{P_m} + h \right)}{\left(\frac{P_i}{P_m} + h \right)}$$

$$A_1 = \frac{A_T \left(\frac{P_o}{P_m} + h \right)}{\left(\frac{P_w}{P_m} + h \right)}$$

$$E_{FL/ph \ 0. \ PF} = E_{NL/ph} \left[\frac{A_x - A_1 - H_d}{A_x - A_1} \right] - I_{ph} \left[R_{ph} + jX_L \right]$$

$$I_{sc} = \frac{E_{NL/ph} \left[\frac{A_x - A_1 - H_d}{A_x - A_1} \right]}{R + jX_L}$$

$$X_d = \frac{E_{NL/ph}}{I_{sc}} \quad \text{ohms}$$

$$X_{dph} = \frac{X_d \text{ ohms}}{E_{ph}/I_{ph}}$$

E_{FL} The voltage supplied to the load at rated current, rated speed, and at a specified power factor.

$$E_{FL} = E_{NL} - I (X_d \sin \theta_{PF} + R_{ph} \cos \theta_{PF})$$

Where X_d = ohms/phase